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OCEAN SURFACE WAVES PRODUCED BY SOME RECENT HURRICANES

ARTHUR PORE

U. S. Weather Bureau, Washington, D. C.

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ABSTRACT

Composite charts of surface wave conditions for several recent hurricanes are presented. The data suggest that the highest average wave height occurs in the right front quadrant as often as in the right rear quadrant. Tide records during two hurricanes when long swells were arriving at the coast are examined for an effect of swell on the tide level.

1. INTRODUCTION

Among the elements of a hurricane, breaking waves are the most destructive. They often demolish boats, docks, buildings, and other private and public property. Such waves are more destructive when superimposed on an abnormally high tide. Forty to forty-five foot waves were reported by Coast Guard stations in New England during hurricanes Carol and Edna of 1954. More recently, hurricane Greta of November 1956, which passed several hundred miles north of Puerto Rico, produced the highest seas in the memories of the inhabitants of the southern and western coasts of Puerto Rico. Thirty-foot swells were reported crashing on the reefs along the southern and western shores and 16- to 20-foot waves were observed along the northern shore after the storm passed north of the island.

The purpose of this study is to present a descriptive view of surface wave conditions in some recent hurricanes with emphasis on two aspects: (1) areal distribution of wave conditions, and (2) propagation of swell and its effect on tide level.

2. RELATED STUDIES

Cline [3] in 1920 concluded that the highest waves and swell are produced in the right rear quadrant of the hurricane and that these waves advance through the smaller waves of the forward portion of the storm, keeping the direction of the motion at the time of wave generation. The basis for this conclusion is that the winds on the right side of the storm blow in about the same direction as the storm movement, thereby permitting longer fetches, longer duration times, and higher wind speeds to exist in the right quadrants of the storm.

Tannehill [7] prepared a composite chart from twelve synoptic maps showing observations of wind and swell directions for the Atlantic hurricane of August 1935. The observations showed that the direction of the swell deviated to the right of the wind. The largest average deviation was in the left rear quadrant, whereas the smallest average deviation occurred in the right rear quadrant. The two front quadrants had intermediate average deviations of about equal magnitude. It was concluded that the deviations of the swell from the wind in the various parts of the hurricane are dependent on the movement of the storm. He also found that to the rear of the storm path there is a line of discontinuity in the direction of swell.

The Scripps wave forecasting theory was adapted [8] to the estimation of waves in hurricanes by dividing the storm into sectors with constant wind direction in each sector and with wind speed dependent on the distance from the storm center.

Arakawa and Suda [1] have presented composite charts of wind speed and direction, state of the sea, and swell for the typhoon of September 26, 1935, over the North

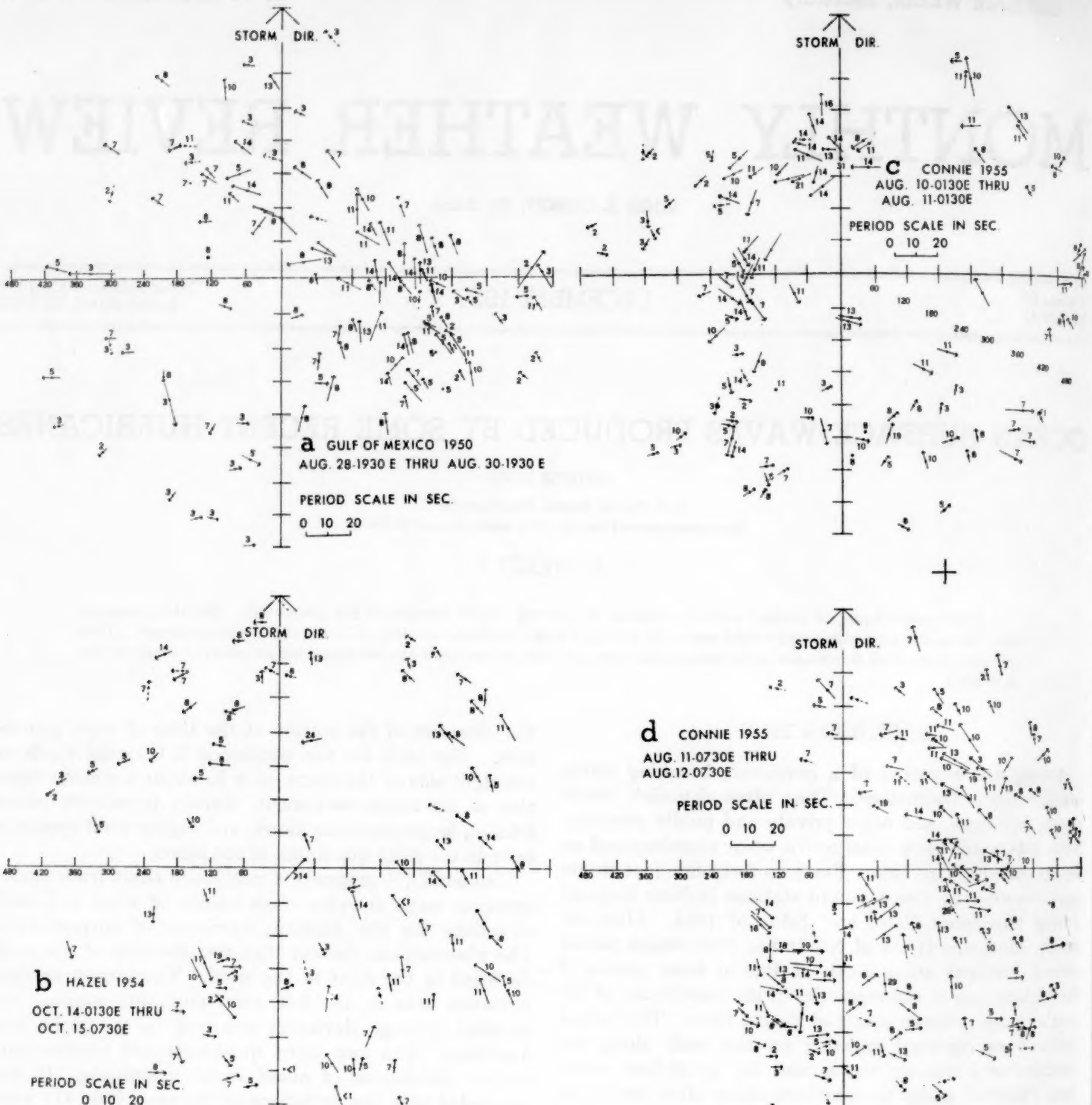

Figure 1.—Composite wave charts. The wave height in feet is plotted beside the arrow indicating direction from which the waves came. The length of the arrow is proportional to the wave period. Dashed arrow indicates unknown period. Distances are marked along the radii at intervals of 60 nautical miles.

Pacific just east of Japan. This storm passed over a main squadron of the Japanese Navy and consequently the wave conditions within the storm were relatively well recorded. They found that the highest waves occurred in the right rear quadrant. Their composite chart of swell showed that among the high swell (greater than 12 feet), the longest occurred in the right rear quadrant.

Arakawa [2] has pointed out that in a limited area of the right rear quadrant the directions of the swell deviate to the left of the wind directions, whereas they deviate to the right within most of the storm area. In the limited area where the directions of the swell deviate to the left of the wind directions, pyramidal waves are produced by the interaction of the swell and the wind waves.

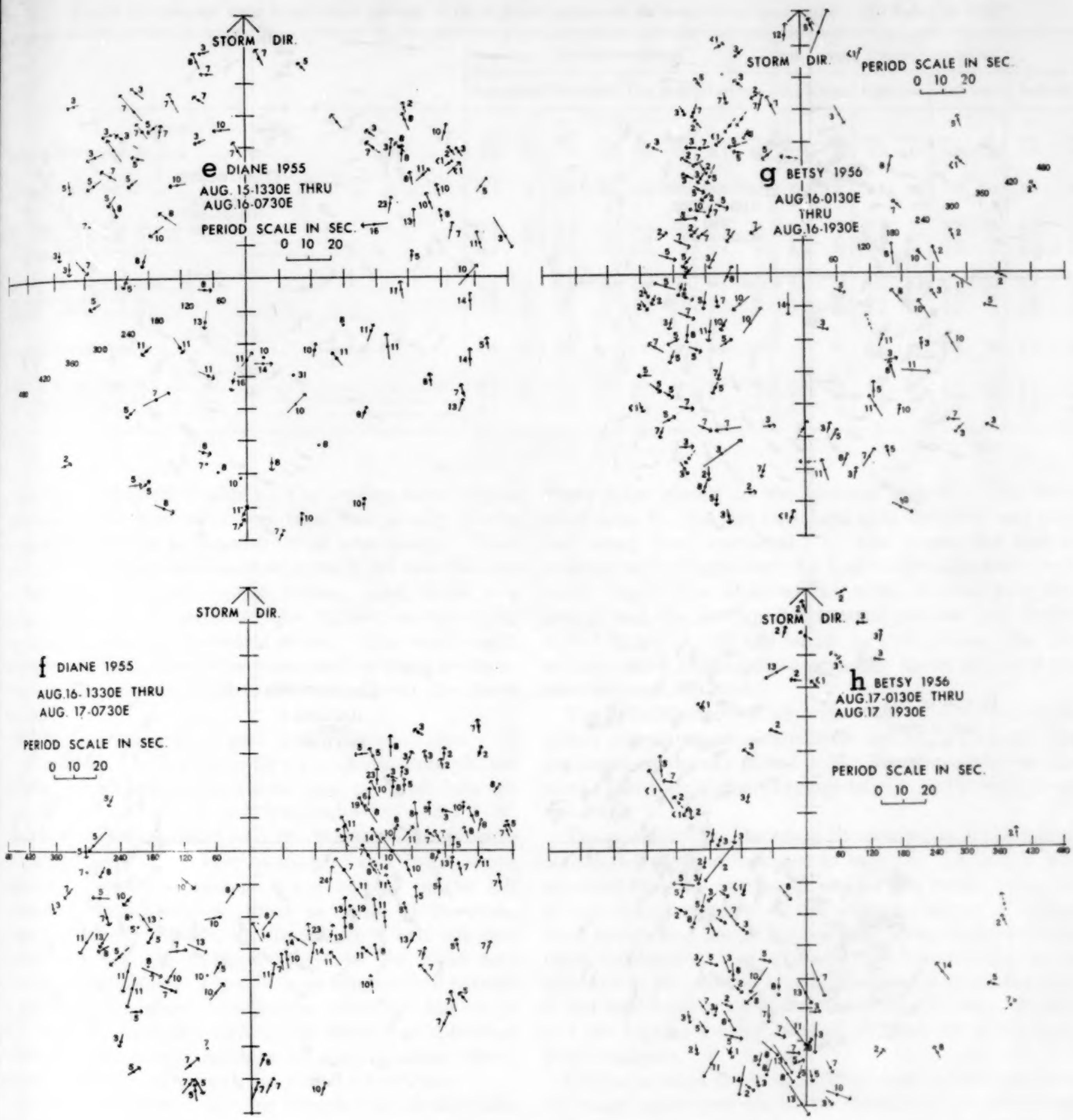

FIGURE 1—Continued.

3. AREAL DISTRIBUTION OF WAVE CONDITIONS

Synoptic charts of ship observations have been plotted to study the wave conditions of some recent hurricanes. The synoptic reports and the ships' records of weather observations include observations of wave direction, wave height, and wave period. No distinction is made in these reports and records between sea (waves produced by the local wind) and swell (waves which have propagated out of the generating area). Certainly, wave direction, height, and period are among the more difficult parameters to observe accurately. The subjectivity of visual wave observations has been pointed out by Pierson, Neumann, and James [5] who state, "The procedure is often for some observer to look out over the sea surface and make a

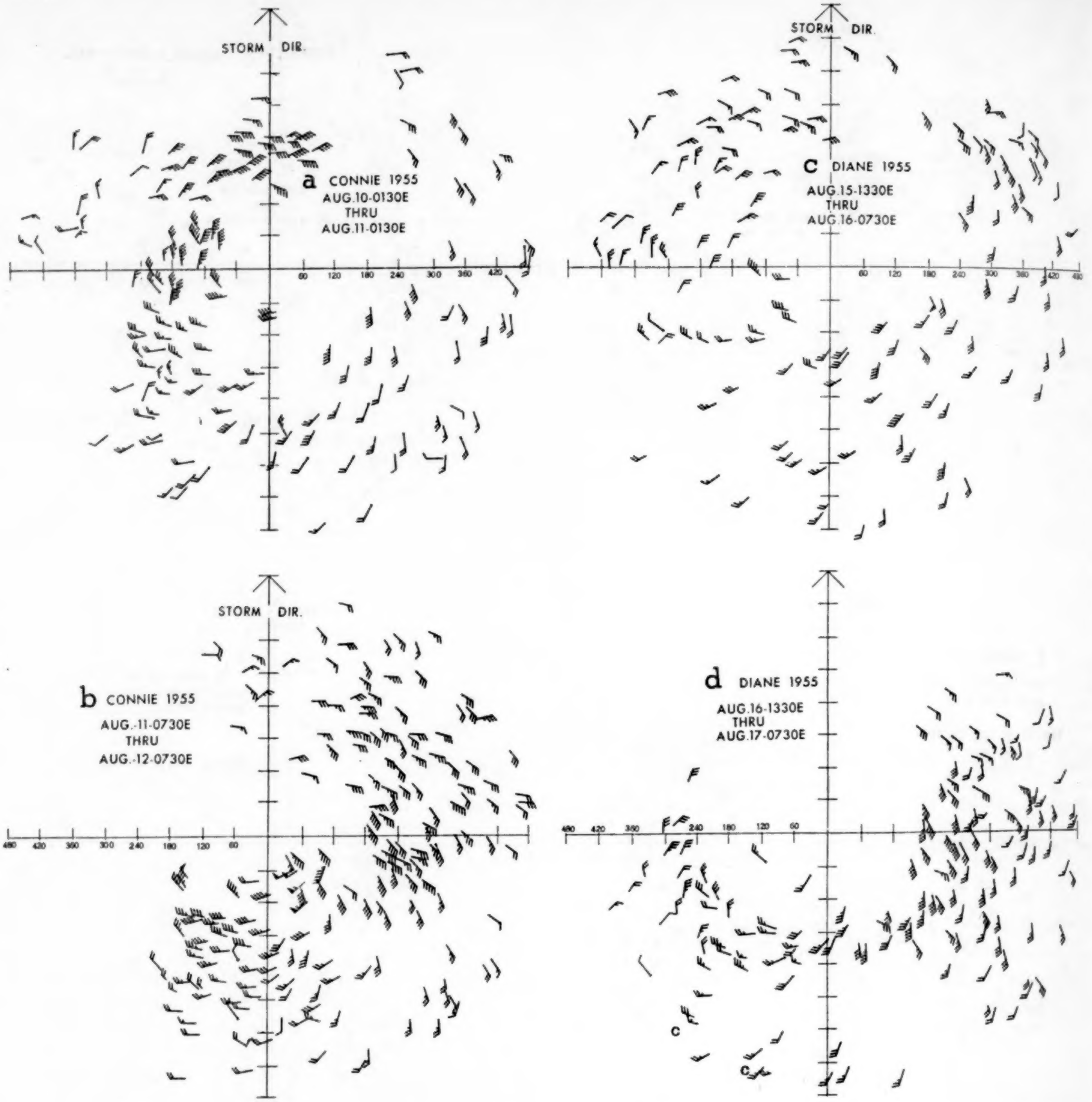

FIGURE 2.—Composite wind charts for hurricanes Connie and Diane, 1955. Wind speeds are plotted in Beaufort force. Distances are marked along the radii at intervals of 60 nautical miles. Calm is indicated by C.

quick guess as to the wave height." The subjectivity involved in making them must be kept in mind when working with wave observations and some discrepancies are to be expected.

Composite charts of wave conditions out to 480 nautical miles from the centers of the storms were prepared by aligning the direction of motion of the storm on the synoptic charts and keeping the location of the storm center constant on the composite charts. The composite charts (fig. 1a-h) show the directions from which the waves came, the wave heights in feet, and the periods in seconds. Wave observations usually are not available near storm centers and therefore the highest waves are probably not indicated on the composite charts. Composite wind charts (fig. 2a-d) were prepared in the same manner for hurricanes Connie and Diane of 1955.

The average wave heights, wave periods, and number of observations considered in each quadrant of several

TABLE 1.—*Average wave heights and periods in the different quadrants in some recent hurricanes. All times in EST*

	Average wave height								Average wave period							
	Right front		Right rear		Left front		Left rear		Right front		Right rear		Left front		Left rear	
GULF OF MEXICO, 1950	*ft.*	*ob.*	*ft.*	*ob.*	*ft.*	*ob.*	*ft.*	*ob.*	*sec.*	*ob.*	*sec.*	*ob.*	*sec.*	*ob.*	*sec.*	*ob.*
1930, Aug. 28–1930, Aug. 30	9.0	24	7.4	45	7.1	26	4.1	17	11.0	25	8.0	48	8.8	23	6.6	16
HAZEL, 1954																
0130, Oct. 14–0730, Oct. 15	9.1	21	8.0	29	6.6	21	7.6	18	7.9	21	9.1	28	6.2	18	7.9	18
CONNIE, 1955																
0130, Aug. 10–0730, Aug. 12	9.6	72	8.9	84	8.5	35	8.5	62	8.5	69	8.3	79	8.6	35	8.2	60
0130, Aug. 10–0130, Aug. 11	10.4	18	8.2	28	9.0	30	7.4	32	9.2	17	7.7	27	8.8	31	7.7	30
0730, Aug. 11–0730, Aug. 12	9.3	54	9.2	56	5.2	5	9.6	30	8.3	52	8.6	52	7.3	4	8.8	30
DIANE, 1955																
1330, Aug. 15–0730, Aug. 17	7.2	67	10.0	70	5.6	36	7.7	59	7.4	68	7.9	64	7.5	36	7.7	52
1330, Aug. 15–0730, Aug. 16	7.3	28	10.7	23	5.6	33	8.2	21	7.6	29	7.2	21	7.5	33	7.1	17
1330, Aug. 16–0730, Aug. 17	7.2	39	9.7	47	5.0	3	7.5	38	7.2	39	8.3	43	7.7	3	8.0	35
JANET, 1955																
0130, Sept. 23–0130, Sept. 28	5.0	32	6.1	49	5.0	32	3.0	31	6.8	28	6.9	49	6.8	29	6.2	23
BETSY, 1956																
0130, Aug. 16–1930, Aug. 17	3.6	19	6.4	43	4.1	58	5.5	92	6.8	19	7.4	42	6.3	54	7.4	91
0130, Aug. 16–1930, Aug. 16	4.3	12	6.4	28	4.5	41	5.3	42	7.7	13	7.1	28	6.0	38	7.0	42
0130, Aug. 17–1930, Aug. 17	2.3	7	6.3	15	3.2	17	5.6	50	5.0	6	8.0	14	7.1	16	7.8	49

storms are contained in table 1. The average wave heights determined are somewhat less than one usually thinks of as being present in the vicinity of a hurricane. However, these averages are based on reports out to a distance of 480 miles from the storm center. Also, there is a definite absence of data on the highest waves which would occur close to the storm center. The wave height averages (table 1) should be considered as being averages over the distance from 60 to 480 miles from the storm centers.

Hurricane Connie of August 1955 progressed slowly off the Carolinas, and ten synoptic wave charts were plotted for the period when the storm was centered between latitudes 30° and 35° N. and longitudes 75° and 77° W. The right front quadrant had the highest average wave height, 9.6 feet. The wave pattern of this storm seems unusual in that the average wave heights in the left quadrants were nearly as great as those of the right quadrants, being 8.5 feet in the left front and left rear quadrants, and the average height in the right rear quadrant was 8.9 feet. The relatively symmetrical pattern of wave heights about Connie was probably due to its slow forward speed of 5 to 8 knots, which would tend to reduce the differences between fetches, duration times, and wind speeds on the two sides of the hurricane.

The synoptic wave charts for Connie were divided into two groups to determine if the average wave heights in the various quadrants were relatively consistent with time or were rapidly changing. The first group was from 0130 EST August 10 through 0130 EST August 11, and the second from 0730 EST August 11 through 0730 EST August 12. The average wave heights as indicated in table 1 for these two periods were not very different, suggesting that the wave height conditions did not change considerably from one day to the next. The value of 5.2 feet for the left front quadrant for the second period is not significant, being based on only five observations.

The pattern of waves produced by hurricane Diane conforms more closely to the classical pattern. The wave conditions for the last two days that the path was over the ocean were examined. In this storm the highest average wave height was 10.0 feet in the right rear quadrant. Again the observations were divided into two groups and the average heights and periods were determined (table 1). It was found, as with Connie, that the average wave heights did not change materially over the time interval involved.

The tabulations of table 1 show that the wave heights in half the storms considered were higher in the right rear quadrant, as usually stated in the literature, whereas the others had their highest average heights in the right front quadrant.

The average wave periods of the quadrants of the storms considered are also included in table 1. At first it was expected that the average of the periods would be higher in the right quadrants of the storms, because of higher wind speeds and longer fetches and duration times of the right quadrants. The average periods were not much different in the various quadrants, usually being between 6 and 9 seconds. However, the Gulf hurricane of 1950 had the highest average period, 11 seconds, in the right front quadrant.

Graphs of wave height and period against distance from the storm center were plotted for several storms and showed little variation of height and period with distance. Although the storms considered were not stationary, the small variations of wave heights and period with distance from the center agree qualitatively with the results for a stationary storm given in [8]. In that study the constancy of height and period with distance are explained by the fact that the decrease in wind velocity with increasing distance is nearly compensated for by the increase in fetch.

4. HURRICANE SWELL AND ITS EFFECT ON TIDE LEVEL

Often a gradual rise of water level is observed at coastal

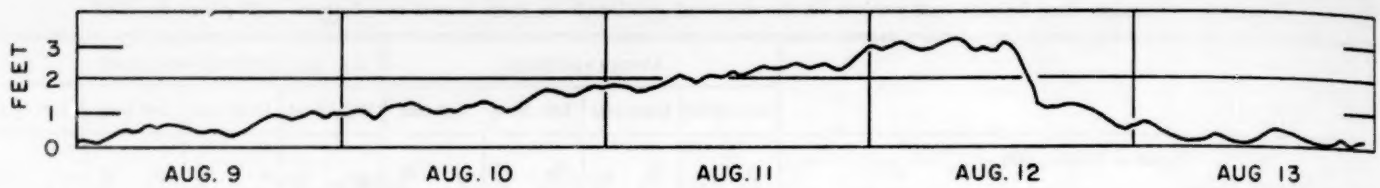

Figure 3.—Abnormal tide (difference between observed and predicted tide), Morehead City, N. C., hurricane Connie, 1955.

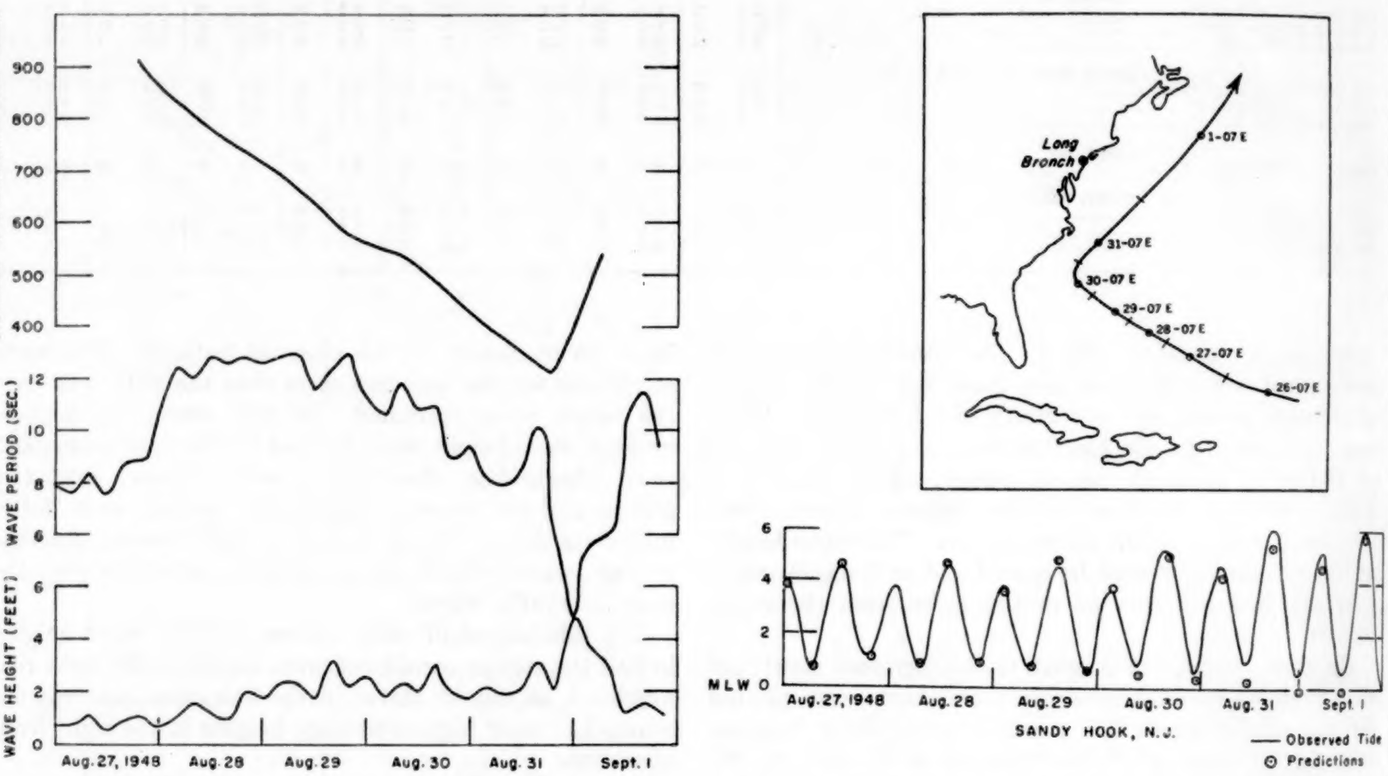

Figure 4.—Significant wave heights and periods recorded at Long Branch, N. J., by the Beach Erosion Board during a hurricane in August 1948. Observed tide curve and predictions of high and low tide are for Sandy Hook, N. J.

stations long in advance of the landfall of a hurricane (Redfield and Miller [6], Willett [9]). Cline [3] has attributed the rise in sea level to the transport of water by swells which are generated within a hurricane and propagate out in advance of the storm. Figure 3 shows the difference between the actual water level and the normal water level at Morehead City, N. C., during hurricane Connie of 1955. In this case the abnormal tide began to build up on August 9, three days before the storm came inland. Figure 4 shows the heights and periods of the significant waves, as recorded at Long Branch, N. J., by a Beach Erosion Board wave recorder, and the distance of the storm center during an Atlantic hurricane of August 1948. The curves show increases in significant height and period while the storm was quite distant. The tide record and the tide predictions for Sandy Hook, N. J., are also presented in figure 4. Practically no abnormality occurred in the observed tide during the time that the long-period waves were recorded.

The heights and periods of the significant waves were recorded by the Beach Erosion Board at Melbourne Beach, Fla., during the period of an Atlantic hurricane in September 1951 and are shown in figure 5. The periods of the significant waves were considered as being a measure of the group velocity of the swell propagating from the storm. The group velocity is given by $C_g=1.52T$, where C_g is the group velocity in knots, and T is the wave period in seconds. According to Deacon [4] the speed with which waves advance through an ocean is within 5 percent of the theoretical group velocity as specified by the wave period. This estimate of wave velocity must be somewhat approximate when based on the significant wave period as it underestimates the velocity of the longer waves and overestimates the velocity of the shorter waves.

The distance to the storm at 4-hour intervals was measured and the travel times of all possible waves (considering the range of observed significant periods) were computed (time=distance/group velocity). Comparison was made between the observed wave velocities (based on the observed periods) and the computed wave velocities which would be necessary for waves of a particular period

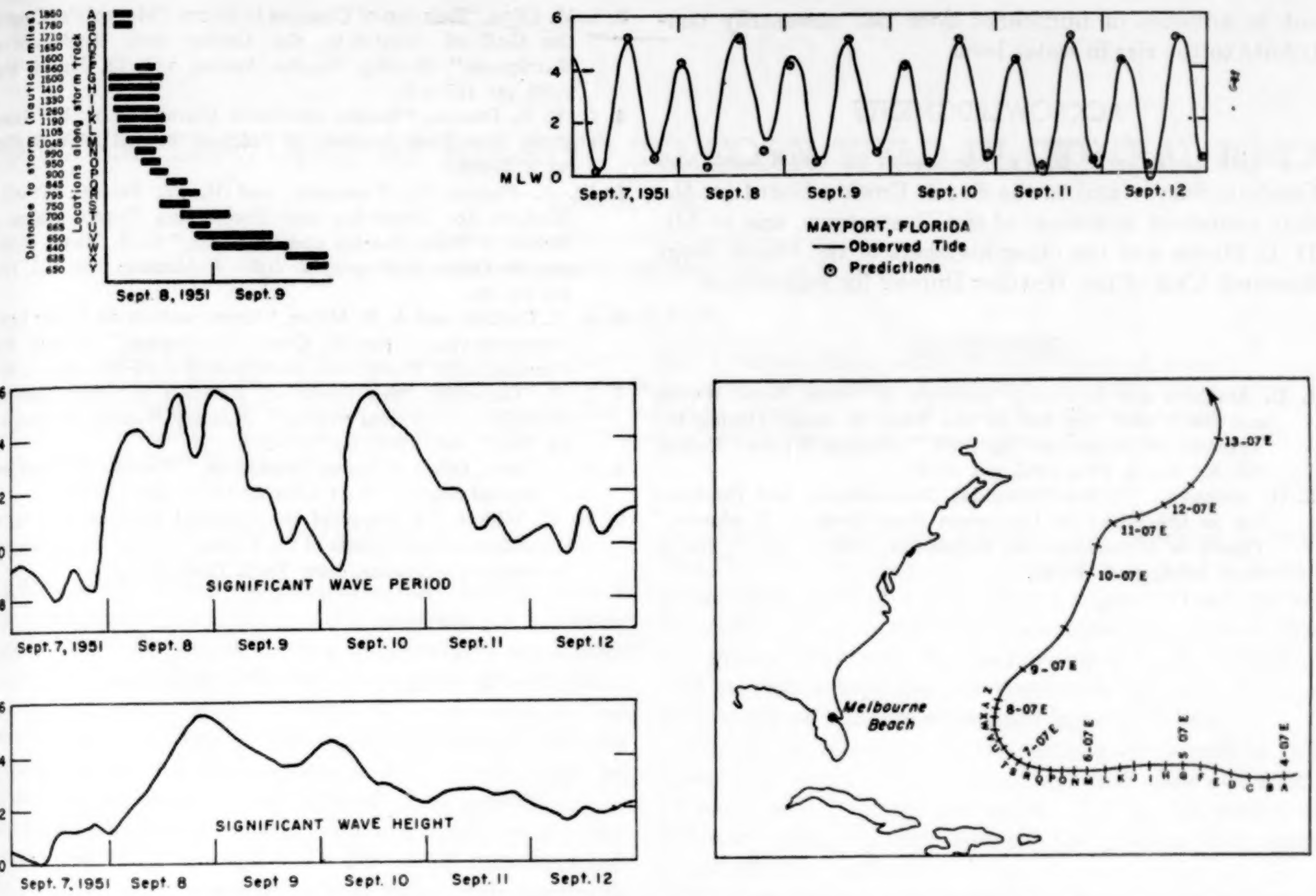

FIGURE 5.—Significant wave heights and periods recorded at Melbourne Beach, Fla., by the Beach Erosion Board during period of a hurricane of September 1951. The bar graph shows the possible locations of the storm that could account for the waves that were recorded at the various times indicated on the abscissa. A location was considered as possible when the wave velocity based on the recorded period agreed within one knot with the theoretical wave velocity based on group velocity and distance to the storm. For example, the waves recorded on September 9 at 2000 EST probably originated at location X along the storm path. Observed tide curve and predictions of high and low tide are for Mayport, Fla.

to be observed at a particular time. It seemed reasonable that, if the computed and observed wave velocities were within one knot of each other, the observed waves could have originated at the location being considered in that instance. Figure 5 includes the path of the September 1951 hurricane, the distance to the storm at 4-hour intervals, and the periods and heights of the significant waves. The bar graph shows the possible locations of the storm that could account for the waves that were recorded at the various times indicated on the abscissa. The locations of the storm center are indicated on the storm track by alphabetical symbols. Because 4-hour positions of the storm were considered in this graph, a 2-hour extension has been added to each end of the components of the bar graph. This makes no component less than 4 hours duration. Also the distance to the storm center locations are shown along the ordinate. This figure shows that the swell arriving at some periods originated at a location over a long stretch of the storm path, whereas at other times the waves must have originated at a location within a much shorter stretch of the storm path. Although swell of this type has been suggested as a cause of abnormally high water levels along a coast due to mass transport of water, the tide record for Mayport, Fla., included in figure 5, shows no abnormality during this period.

The tide records for the two storms discussed above indicate that swell arriving from hurricanes does not necessarily cause abnormally high tide levels. These data support the observations of Redfield and Miller [6] that the rise in water level ahead of a hurricane is dependent on the wind field into which the storm is advancing.

5. SUMMARY

The data suggest that the highest values of the wave heights from 60 to 480 miles from the storm center occur with about equal frequency in the two right quadrants. Also the wave conditions of mature hurricanes do not change materially from one day to the next. Comparison of wave and tide records indicates that swell propagating

out in advance of hurricanes does not necessarily contribute to the rise in water level.

ACKNOWLEDGMENTS

I wish to express my appreciation to the Coast and Geodetic Survey and to the Beach Erosion Board for the data contained in several of the illustrations, and to Mr. D. L. Harris and the other members of the Storm Surge Research Unit of the Weather Bureau for suggestions.

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SOIL TEMPERATURES AS RELATED TO CORN YIELD IN CENTRAL IOWA

JOHN A. RILEY, JR.

Weather Bureau Airport Station, Des Moines, Iowa

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ABSTRACT

Soil temperature data collected at the Iowa State College Agronomy Experimental Farm are analyzed in relation to corn yields. Some of the determining weather factors of soil temperature are evaluated. Monthly values of soil temperature at various levels are compared with corn yield in central Iowa and three physical relationships are discussed. In order to summarize the effect of these three relationships, a regression equation for the forecast of corn yield is proposed.

1. INTRODUCTION

Information on soil temperatures may well provide a key to increased corn yield and a program for lessening crop failure. These sub-surface temperatures are known to exert a controlling influence over plant growth from plowing and planting time to harvest. It is believed that the methods described in this report, concerned with the relationship of soil temperature to corn yield, could be adapted to the study of any type of plant growth.

Soil temperature measurements and analyses are not new. Over 100 years ago J. D. Forbes [4] measured soil temperatures at three locations near Edinburgh, Scotland, for varying depths down to 24 feet. The conclusions he drew then as to temperature waves and their propagation with increasing depth are still valid today. However, the use of this type of data has been largely neglected and only in the last few years is a systematic network of observations being attempted. The following report is preliminary and points to the vast potential usefulness of soil temperature data in modern agricultural research.

The purpose of this report is to examine the relation of soil temperature to corn yield in central Iowa. The regression equation for the forecast of corn yield is given to summarize the effects of soil temperature alone. The accuracy of the forecast could be improved by including other elements, such as soil moisture, but that is not the aim of this study.

Soil temperature data were obtained from the Agronomy Farm weather station, 4 miles southwest of Ames, operated cooperatively by Iowa State College, the Iowa Department of Agriculture, and the U. S. Weather Bureau. The Webster silty clay loam soil is fairly typical of Iowa's better farm land of recent glacial origin. Readings are taken from long mercury thermometers that extend into the ground but may be read without being extracted. The ground is kept bare of vegetation and is cultivated to a depth of 2 inches after each important rain.

The period of record for the various levels used in this report is given in table 1. Readings were made at 7 a. m., 12 noon, and 7 p. m. CST except during the period of February 1942 through August 1945, when they were taken one hour earlier.

The average soil temperature for the periods indicated will be referred to hereafter as the mean. In order to utilize the entire record of soil temperature data as listed in table 1 for analyses described in the last two sections, it has been necessary to adjust the temperature of the 1-inch level for the 4-year period when observations were taken 1 hour earlier, and of the 24-inch and 48-inch levels, since readings for the last 3 years were at 20 and 40 inches, respectively. In most cases the adjusted means were the same and in no case did the change amount to more than 1°. The final computations presented in sections 3 and 4 are based on the 7 a. m. readings and no adjustment was made to the original data.

2. SOIL TEMPERATURE AS A COMPONENT OF CORN DEVELOPMENT

Figure 1 gives a chronological comparison of soil temperatures and corn development and as such contains much of the data basic to this study.

TABLE 1.—*Period of record of soil temperature readings*

	Depth (inches)										
	1	2¾	4	6	8	12	20	24	40	48	72
Began	July 1937	April 1946	November 1949.	July 1937	November 1949.	July 1937	November 1949.	July 1937	November 1949.	July 1937	July 1937.
Ended	1953	1953	1953	October 1949.	1953	October 1949.	1953	October 1949.	1953	October 1949.	1953.

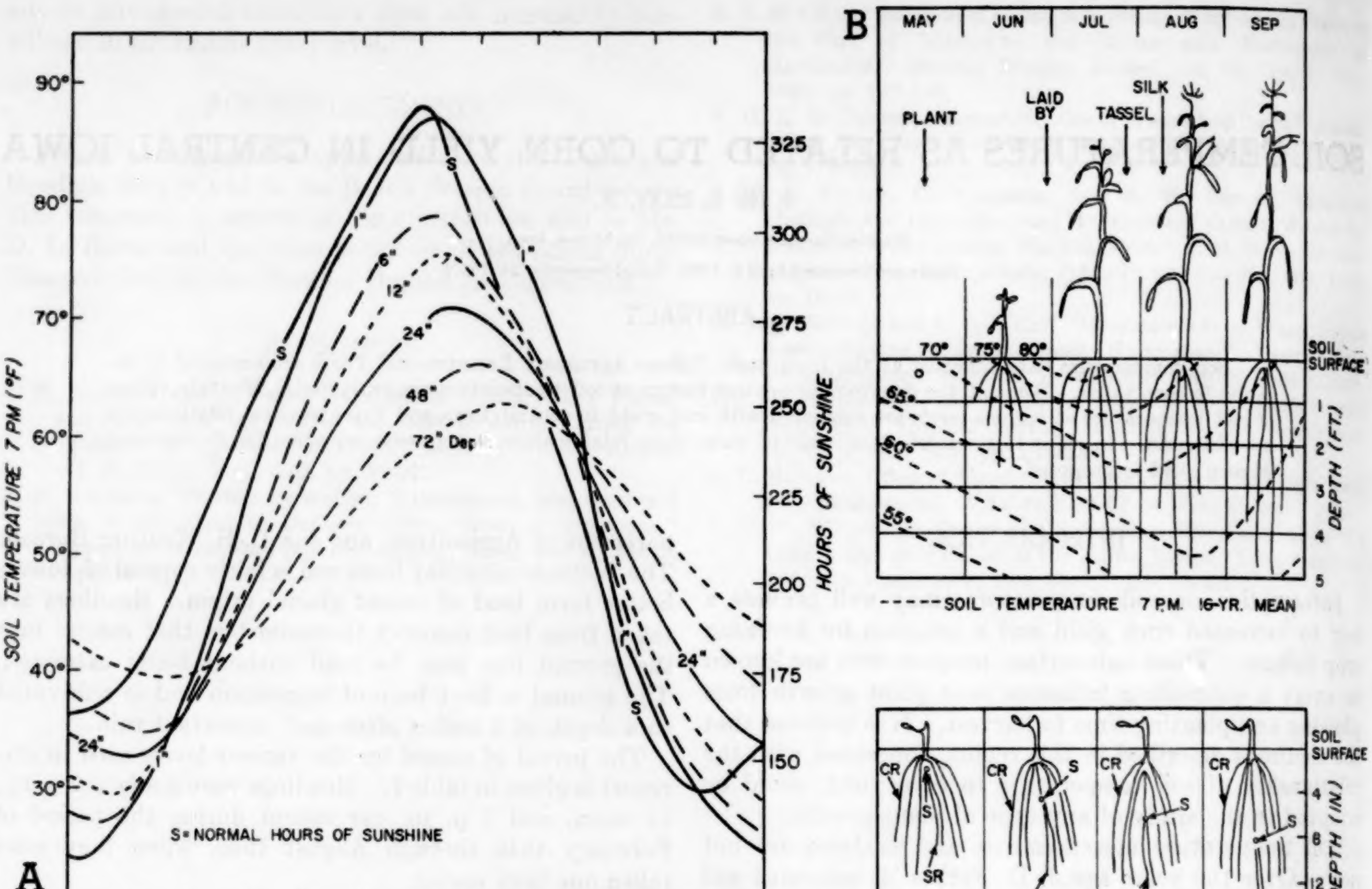

FIGURE 1.—Soil temperature as a component of corn development. (A) Mean annual soil temperature waves (1938–53) and normal annual hours of sunshine. (B) Schematic diagram of corn development compared with mean soil temperature of various depths and months. (C) Root development. The majority of roots (coronal roots) arise at the subcrown internode, about an inch below the soil surface, regardless of the depth the seed is planted.

The schematic drawing of corn growth in figure 1B emphasizes the most important phases of the plant's life cycle. The seed is planted 2 to 3 inches deep about May 15. The soil temperature in the seed bed should be in the upper 50's (°F.) or higher for proper germination [23], and as shown in the figure, usually it is in the upper 60's. The crop is normally laid by (receives its last cultivation) by the first of July. During the time of tasseling, July 20–25, and silking, August 5–10, the plant is particularly sensitive to the weather [16, 18].

Another important factor in this study is root development. Figure 1C illustrates the two types of roots produced by corn [11]. The seminal roots develop from the lower end of the embryo and though they often penetrate to depths of 5 to 6 feet and remain active until the plant matures, the coronal roots which arise at the subcrown internode become more important once they are established. Regardless of the planting depth, the main mass of roots joins the plant about 1 inch below the soil surface, making the temperature at that level of great importance throughout the entire growing season. During the first weeks of the plant's life, underground growth is faster than above ground. By the latter part of June the roots normally have penetrated to a depth of 2 feet. The roots usually grow 5 to 6 feet deep [5]; however there are exceptions due to extremes in soil moisture, soil density, and plant variety.

Figure 1A contains graphs of the normal hours of sunshine and the annual soil temperature waves. The soil temperature curve at 1 inch closely follows curve S, the normal hours of sunshine, and the main difference between the other temperature curves is a damping of the amplitude and a lag of the time of the maximum and minimum temperatures with increasing depth. The tracing of the mean 60° and 75° F. isotherms is of paramount importance. The temperature reaches 60° at the 2-inch level in April, at the 2-foot level in May, and at the 6-foot level in July. This sequence precedes seed and later root development by 3 to 6 weeks. The 75° isotherm appears near the surface in early June and disappears in late August. Normally its maximum penetration is a little over 12 inches in July. In section 4 it is shown that displacement of these two lines is associated with corn yield.

Figure 2 focuses attention on some of the problems

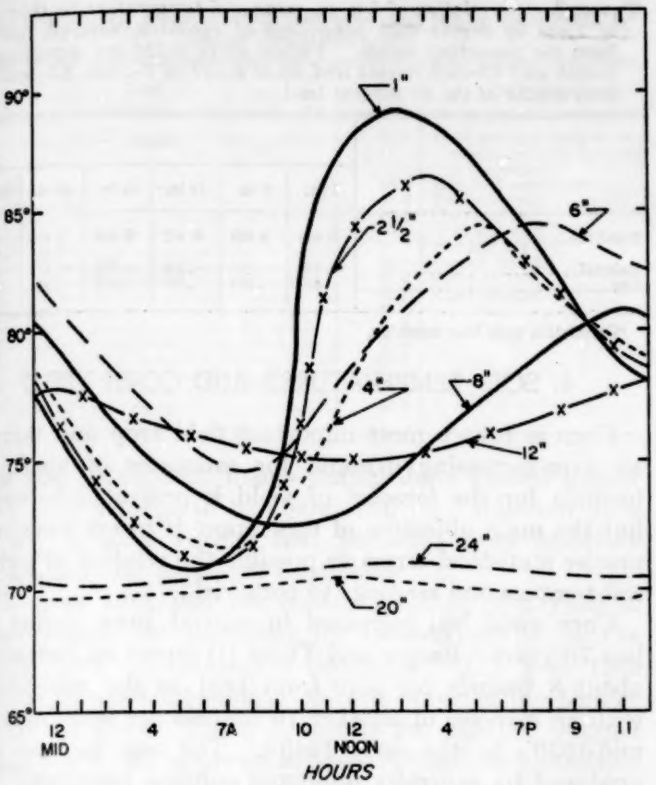

FIGURE 2.—Mean diurnal temperature waves for various depths for the month of July (1938–53 or less) showing time of maximum temperature.

encountered in summarizing and using soil temperatures. Maximum and minimum readings are usually lacking and if available would occur at different times for different depths. In the first 12 inches, the noon reading is closest to the mean temperature [19], but the sharpness of the temperature rise at that time, as compared with either 7 a. m. or 7 p. m., subjects the noon observation to more fluctuation. As indicated earlier, the different times of readings used in this report would require a correction factor for the evening data which may be ignored with the morning temperatures; the 7 a. m. data are used in sections 3 and 4. The lower temperature at 20 inches than at 24 inches may be accidental because data for different periods of record were used for the two levels.

In comparing figures 1 and 2, it will be noted that the mean temperature at the 1-foot level rises about 7° from June to July; while the diurnal change during the month of July is only about 3°. For levels near the surface this is reversed. At 6 inches, the monthly change from June to July is also 7°, but the diurnal change during July is 10°. For readings below 6 inches, diurnal changes can be assumed minor as compared with monthly changes.

3. FACTORS DETERMINING SOIL TEMPERATURE

To interpret properly relations of soil temperature to corn yield it is desirable to have a practical understanding of the relation of some easily measured weather elements with soil temperature. The elements considered in this report are air temperature, percent of sunshine, rainfall, and persistence.

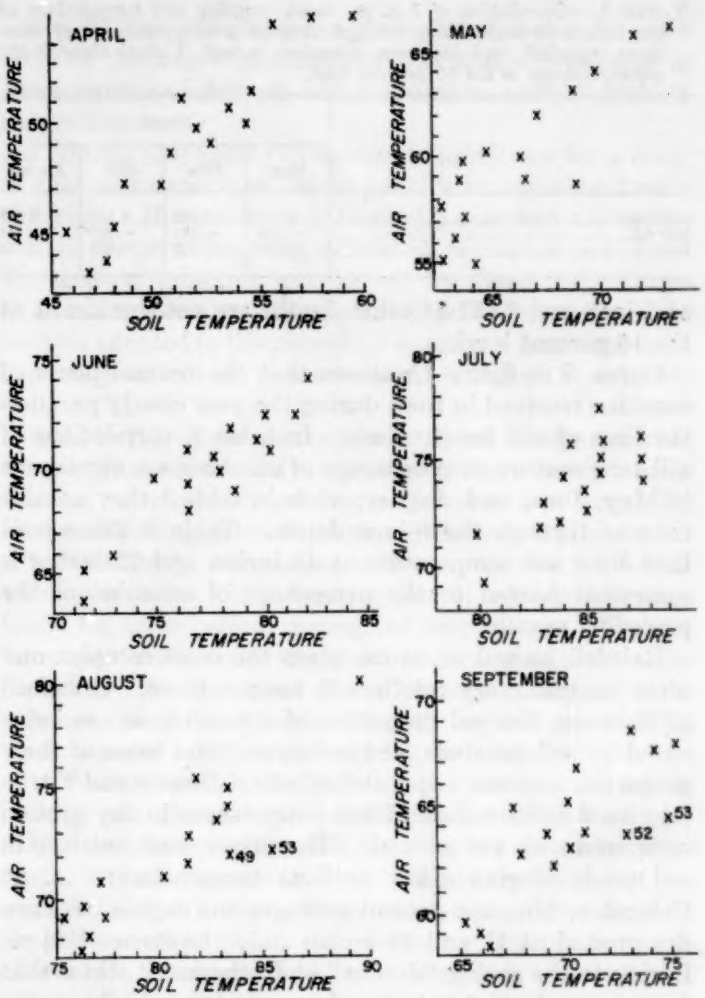

FIGURE 3.—Mean monthly air temperature compared with 7 p. m. 1-inch soil temperature, April through September (1938–53).

The relation of soil temperature (surface) to air temperature is shown in figure 3. Neither is the sole cause or result of the other, but both result from the same environment. Much of the variation is caused by soil moisture, which affects the thermal properties of the ground. For example, Iowa had very dry weather during August 1949, September 1952, and August and September 1953. As shown in figure 3, the soil temperature for those months was much higher than the air temperature when compared with the same months in other years. For this reason, and by correlations presented later, soil temperature may be considered as a better measure of drought than air temperature.

Table 2 shows the correlation of the mean 1-inch 7 a. m. soil temperature for May through August at Ames with (1) percentage of sunshine at Des Moines; (2) rainfall at Ames (to give further weight to very dry weather, rainfall was arbitrarily classified: 1 unit for each ½ inch up to 2½ inches, 1 unit for each inch from 2½ to 7½, and 1 unit for each 2 inches above 7½ inches); (3) lag in soil temperature, which is the persistence from one month to the next. Table 3 contains the same weather elements and their relation to depth for the month of June. For the number of observations available, correlation values less than 0.426

Table 2.—*Correlation of 7 a. m. mean monthly soil temperature at the 1-inch level for May through August with percentage of sunshine, rainfall, and lag from preceding month. Values above 0.426 are significant at the 10 percent level.*

	Month			
	May	June	July	August
Sunshine	0.677	0.556	0.310	0.547
Rainfall	−.314	−.185	−.207	−.344
Lag	.143	.417	.669	.352

at 1 inch and 0.497 at other depths are not significant at the 10 percent level.

Curve S in figure 1A shows that the normal hours of sunshine received in Iowa during the year closely parallels the lines of soil temperature. In table 2, correlations of soil temperature to percentage of sunshine are significant in May, June, and August; while in table 3 they are significant through the 6-inch depth. Table 3 also shows that June soil temperature at 48 inches and 72 inches is somewhat related to the percentage of sunshine of the preceding month.

Rainfall, as soil moisture, plays the most complex and often contradictory role in soil temperatures. Crawford [2] lists the thermal properties of the soil that are influenced by soil moisture, and points out that some of these properties may exert opposing effects. Brooks and Fitton [3] give definite values of soil temperature in dry ground compared with wet ground: "The presence of moisture in soil tends to give a low uniform temperature; . . . At Columbia, Mo., wet ground averages one degree less than dry ground at 12 and 36 inches . . ." Lawrence [10] referring to the spring "dryout" at Rothamsted states that frost frequency increases or decreases less rapidly as the soil dries out, in spite of steadily increasing soil temperatures. In general agreement with most investigations it may be stated, assuming many simplifications, that the effect of soil moisture is to stabilize temperatures, offering resistance to change.

Coupled with the varying effects of soil moisture, rainfall has a unique effect on soil temperatures. It is the only cause of large nearly simultaneous temperature change at all depths down to the 2-foot level. Soil temperature changes resulting from the percolation of rain differ entirely from normal thermal diffusion. Rainfall has no significant correlation with soil temperature, but its relation is negative in all months. The low correlations of rainfall with soil temperature are considered to be more a result of the opposing effects mentioned above than of any lack of relation.

The persistence in anomalies of all weather elements is well known. The lag correlation in table 2 is a sum of persistence in causative weather variables and heat storage of the soil. The lag correlation in table 3 steadily increases with depth, until at the 6-foot depth it is significant at the 1 percent level.

The correlations discussed hold little promise for predicting soil temperatures but are summarized here for such value, positive or negative, as they may hold for other attempts of this nature.

Table 3.—*Correlation of 7 a. m. mean soil temperature for the month of June by depths with percentage of sunshine, rainfall, and lag from the preceding month. Values above 0.426 are significant at 1-inch and 72-inch depths and above 0.497 at 6-, 12-, 24-, and 48-inch depths at the 10 percent level.*

	Depth					
	1 in.	6 in.	12 in.	24 in.	48 in.	72 in.
Sunshine	0.556	0.587	0.467	0.465	0.420 *.161	0.221 *.336
Rainfall	−.185	−.195	−.330	−.272	−.272	−.190
Lag	.417	.254	.487	.523	.544	.738

*Correlation with May sunshine.

4. SOIL TEMPERATURES AND CORN YIELD

Corn is Iowa's most important field crop and there is an ever-increasing demand for estimates of yield. A formula for the forecast of yield is presented herewith, but the main objective of this report is to evaluate in as precise statistical terms as possible the relation of certain soil temperature readings to corn yield.

Corn yield has increased in central Iowa during the last 70 years. Barger and Thom [1] report an increase of about 8 bushels per acre from 1891 to the mid-1930's, with an increase of another 10 bushels per acre from the mid-1930's to the early 1940's. The first increase was produced by generally improved cultural practices. The great jump that came in the late 1930's was caused in large part by widespread acceptance and use of hybridization. The data considered here were all obtained during the period of hybridization except for 1938 and 1939. The 1938 and 1939 yields were adjusted upward from 59.3 to 64.0 bushels per acre and from 59.3 to 60.0 bushels per acre as described by Barger and Thom. A linear regression line fitted to yields from 1940 through 1953 indicates a slight decline of about 1½ bushels per acre during this period. The period is too short to indicate a trend, but it has eliminated the need to adjust upward the early yields (with the exceptions of 1938–39). On a national scale, where general acceptance of hybrid varieties came more slowly in the years after 1937, a significant trend in yields might exist.

Table 4 contains the corn yield for the central district of Iowa (Agriculture Marketing Service Crop Reporting District), along with a very simplified list of the major detriments. This district is composed of 12 central counties of Iowa and comprises an area of slightly more than 6,000 square miles. Yields quoted are from the Iowa Agricultural Year Books, except 1938–39 as indicated above.

The first 2 years listed in table 4 deserve special attention. The year 1947 had the most disastrous corn weather in recent years, and the only really poor crop of the period considered. As reported in the Annual Iowa Climatological Summary under direction of Thom [22], "The dependence of Iowa agriculture upon the vagaries of the weather was closely demonstrated during the 1947 season. A cool wet spring delayed crop planting activity and plant growth; then, in addition, a hard freeze on May 29th . . . further set back the corn. The heavy

TABLE 4.—*Corn yield (bushels per acre) and major detriments in central Iowa, 1938–53.*

Year	Yield	Detriment
1947	28.8	Cold and wet early in the season, hot and dry late in the season.
1949	46.0	Dry, and corn borer.
1951	48.9	Cold and wet.
1945	49.1	Cold and wet.
1950	50.2	Cold and wet.
1944	52.4	Hot and dry.
1953	56.0	Partial drought.
1941	57.3	Short drought.
1940	57.7	Short drought.
1939	60.0	
1943	61.2	
1946	63.0	
1938	64.0	
1948	65.0	
1942	66.5	
1952	67.0	

rains and subsequent floods during June caused appreciable crop acreage to be abandoned . . . followed by a hot dry weather regime that persisted from mid-July through the first decade of September."

The year 1949 had the second smallest corn yield in recent years. As described by Lamoureux [9] in the Annual Iowa Climatological Summary, "The year 1949 saw the greatest infestation of corn borer in the history of corn in Iowa. Early prospects for another bumper crop [the yield of the previous year 1948 had been exceeded only once at that time] were canceled by the persistence of dry weather in some sections and by the corn borer pest in all sections."

As far as has been determined, the only other work done relating corn production with soil temperatures was published in 1910 by Hunt [8]. In that report, 4 years of soil temperatures at unspecified levels during 1882–85 were compared with the moisture content of the corn. Low soil temperatures (presumably means for the growing season) were related to high moisture content at harvest time and, while moist corn does not necessarily mean low yield, it may mean a low quality of corn. As shown in section 3 soil and air temperatures differ. Soil temperature can change rapidly under strong solar radiation and air temperature can be modified quickly by advection. Of these the solar heating of soil (and plants) is considered to be the primary influence on crop development. Since soil temperature is a function of many factors it is used as the independent variable in this study without the loss in degrees of freedom which years ago plagued Mattice [12] and others using multiple correlation methods.

While soil temperatures are investigated here, earlier studies of air temperature indicate that plants respond differentially to heat energy available during progressive stages of the growing season. Various investigators have found the following three basic types of relation between air temperature and corn yield:

1. Smith [21] by simple correlation found a high positive relation between corn yield and June temperature in Ohio. Rose [17] obtained the same results later; he also found that within the same State some weather elements correlated positively in some areas and negatively in others. Wallace [23] stated that high correlations were notably lacking in the central corn belt, including Iowa. Later Wallace and Bressman [24] concluded that for most of Iowa the worst corn weather was cool wet weather in May, June, and August, which results in a slight positive correlation.

2. Smith [20] speaks of optimum conditions for a crop, so that any departure, either positive or negative, lowers the yield. Houseman and Davis [7] attacked this problem in western Iowa by means of regression statistics. The general principle was set out by Reed [14]: "Crops in Iowa, under exceptionally intelligent husbandry have become adapted to the prevailing weather. Any important departure above or below normal weather is deleterious . . ."

3. Mills [13] by simple correlation found a large negative correlation between July temperature and corn yield in Kansas. An even larger negative value was found by Hodges [6] using methods of curvilinear regression.

In this study, correlating soil temperature with crop yield, the same three basic types of correlation were found for three periods during the crop season. Figure 4 is composed of scatter diagrams of corn yield versus the departure from the mean of the 7 a. m monthly soil temperature at various levels, May through August. The three types of relationship may be observed:

1. Positive correlation early in the season. All levels in May and the 48-inch and 72-inch levels in June and July show some positive relation; the maximum correlation at 48 inches occurs in June. This is a reflection of the earliness of the season. High soil temperatures early in the season reflect mildly dry weather. One of the worst effects of a wet spring and early summer is that it limits plowing and cultivation. It also retards plant growth. Reed [15] says that most Iowa corn crop losses are caused not by early fall frosts but by the sequence of cold spring weather, late planting, and early frost. On the other hand he points out that a June air temperature 2° or more above normal virtually assures crop maturity ahead of fall frost.

2. Negative correlation with any departure from the mean in the middle of the season. As early as May at 6 inches (fig. 4) maximum yields are associated with temperatures near the mean. Large positive or negative departures are detrimental. Optimum conditions for the crop in the upper 2 feet during June are shown by the negative correlation with departures from the mean and are centered at 12 inches. During June the corn plant grows rapidly and is very sensitive to any extreme conditions. This is the strongest of all correlations; it has not appeared as such in previous investigations. The reason for the high correlation found in this study may be (1) use of soil temperatures instead of air temperatures, or (2) use of hybrid corn which is especially designed for average local conditions. As described in section 2, root development passes through the 1- to 2-foot level in June and is probably the reason that the core of high correlation is near that level. In July and August this negative correlation tendency is not so noticeable.

3. Negative correlation late in the season. In August

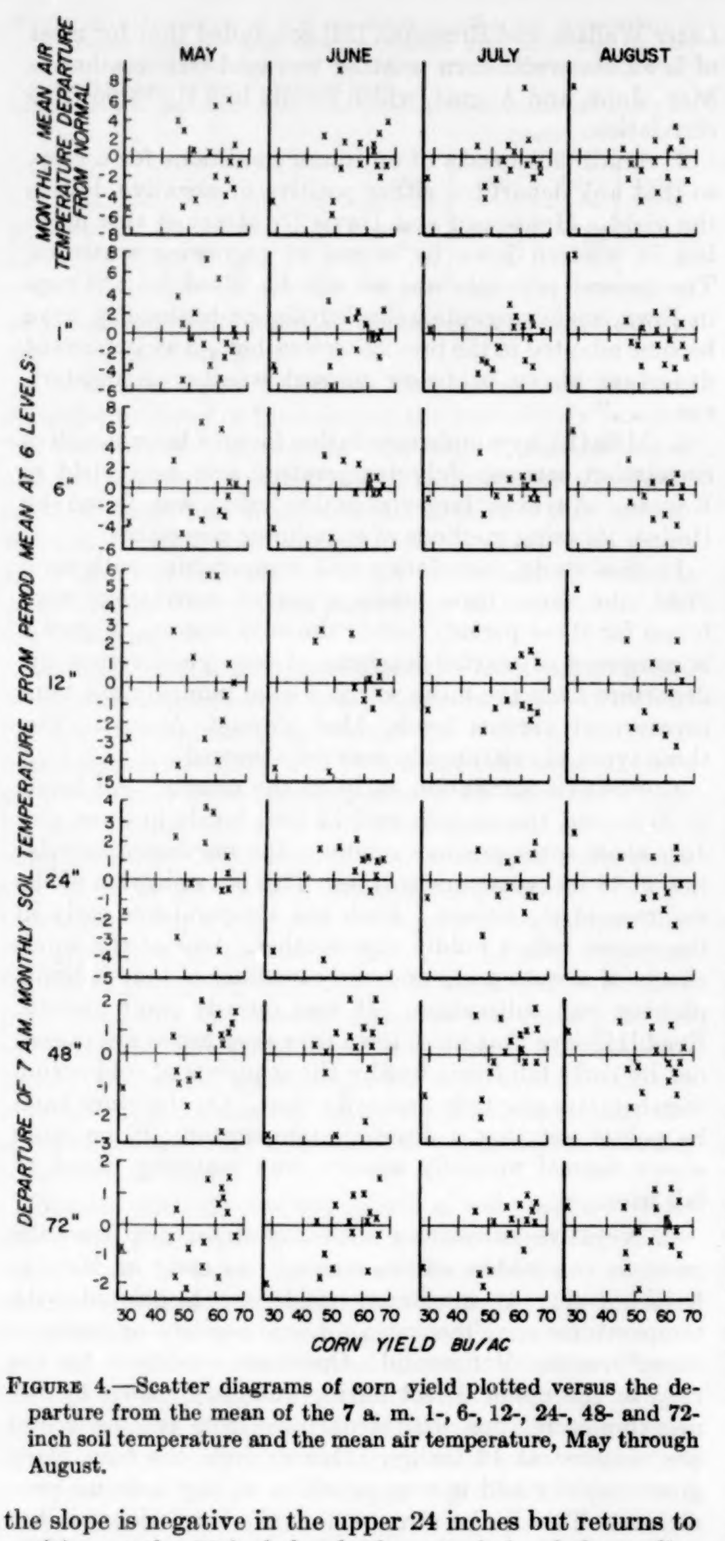

FIGURE 4.—Scatter diagrams of corn yield plotted versus the departure from the mean of the 7 a. m. 1-, 6-, 12-, 24-, 48- and 72-inch soil temperature and the mean air temperature, May through August.

the slope is negative in the upper 24 inches but returns to positive at the 72-inch level, characteristic of the earlier months. This August negative correlation has a peak at the 1-inch level. This may be termed the drought factor. Hot dry weather in August reduces the corn crop considerably, but seldom if ever does soil temperature get low enough in August to be detrimental in central Iowa. This causes the single hot dry August in 1947 to bear much of the weight of the correlation. A somewhat similar case occurred after the period of this study, when lack of rain during July and all of August (the 7 a. m.

TABLE 5.—*Absolute values of simple correlations of corn yield with the 7 a. m. 1-inch through 72-inch soil temperature and the mean air temperature, May through August, showing the centers of the three types of correlation. Unboxed area=positive correlation; Single boxed area=negative correlation with departure from mean of period; Double boxed area=negative correlation. Correlations are significant at the 10 percent level when over 0.425 at the 1- and 72-inch levels and with air temperature, and when over .496 at 6, 12, 24, and 48 inches (data 1938–53, or less).*

	May	June	July	August
Air	0.129	0.511	0.248	0.448
1"	.166	.628	.039	.613
6"	.271	.769	.045	.581
12"	.160	.777	.146	.507
24"	.159	.720	.275	.315
48"	.341	.567	.447	.082
72"	.415	.555	.561	.479

1-inch soil temperature was 3° above normal) reduced a very promising crop in 1955. Two reasons are given for the core of negative correlation at 1 inch: (1) the upper stratum of the ground receives the full heat of sunshine so that during periods of dry weather excessive heating tends to magnify the drought conditions, sometimes resulting in severe damage to the crop; (2) as earlier shown, most of the roots branch off the stalk about an inch below the surface of the soil and are sensitive to the temperature at that level.

Table 5 contains the absolute values of each type of simple correlation with corn yield.

Three groups of data were chosen to represent each type of relationship in order to formulate a basic regression equation: the 72-inch June temperature, the 1-inch 7 a. m. June temperature, and the 1-inch 7 a. m. August temperature. As indicated earlier, readings since 1949 have been taken at the 2¼-, 4-, 8-, 20-, and 40-inch levels instead of the 6-, 12-, 24-, and 48-inch levels computed in this report. That is the reason the 1-inch June reading is used in the regression equation, even though the 12-inch correlation is higher, and similarly, the 72-inch June reading instead of the 48-inch value. When more of the new readings are available, intermediate levels, nearer the cores of the correlations should be used. The following regression equation is the result of the multiple correlation of the three groups of data:

$$X_1=28.0756+3.0272X_2-2.1556X_3-1.9487X_4$$

$s_{1.234}=5.68$ $r_{12}=0.555$ $r_{12.34}=0.323$ $\beta_{12.34}=0.327$

$R_{1.234}=0.811$ $r_{13}=-0.628$ $r_{13.24}=-0.509$ $\beta_{13.24}=-0.356$

$r_{14}=-0.613$ $r_{14.23}=-0.564$ $\beta_{14.23}=-0.538$

where:

X_1 =Corn yield
X_2 =June 72-inch soil temperature
X_3 =Departure from the mean of the June 1-inch 7 a. m. soil temperature
X_4 =August 1-inch 7 a. m. soil temperature
$s_{1.234}$ =Standard error of estimate of regression formula

$R_{1.234}$=Multiple correlation coefficient of regression formula

r_{12} =Simple correlation of 72-inch June soil temperature with yield

$r_{12.34}$ =Coefficient of partial correlation of 72-inch June soil temperature

$\beta_{12.34}$ =Beta coefficient of 72-inch June soil temperature

The coefficient of multiple correlation $R_{1.234}$ is a measure of the combined relation of the three parameters to corn yield. For the 16 years 1938–53, F-tests show it to be significant at the 1 percent level. The statistic r_{12} is the coefficient of correlation of the 72-inch June soil temperature to corn yield, while $r_{12.34}$ is the coefficient of partial or (net) correlation of the same parameter. The latter is the relationship between corn yield and the single independent variable (72-inch soil temperature) when the other two factors included in the study are held constant.

There is a relationship, mainly persistence, between weather phenomena of adjacent months and it is not surprising that there is a considerable interrelation between the three parameters used in the above equation. All the partial correlations show smaller values than the simple correlations for the same variables. It is shown that the net effect of 72-inch June soil temperature upon corn yield is distinctly less than was indicated by the simple correlation.

The 1-inch June soil temperature shows the highest correlation when considered alone, but after the effect of the other two variables has been minimized, the partial correlation ranks second to the 1-inch August soil temperature. The June 1-inch variable has been measured as a departure from the mean; and the partial correlation of this variable has a relation to below normal temperatures of the 72-inch June variable and a relation to above normal temperature of the August 1-inch variable; thus generally speaking, the middle variable was reduced more than the other two variables, and may rank somewhat higher than the partial correlation indicates.

Beta coefficients are another expression of the relationship between the variables. $\beta_{12.34}=.327$ may be taken to mean that with a decrease of one standard deviation in June 72-inch soil temperature, when the other two factors are held constant, the corn yield decreases .327 of one standard deviation. Putting this in the original dimension and holding the other variables constant: a decrease of 1° at 72 inches in June will decrease the yield by 3.13 bushels per acre; a displacement of 1° away from the mean of the June 1-inch soil temperature, either above or below, will decrease the yield by 2.16 bushels per acre, and an increase of 1° of the August 1-inch soil temperature will decrease the yield by 1.95 bushels per acre.

The following is an example of the proposed formula applied to independent data, 1954. Yield that year was 56.2 bushels per acre or just slightly above the normal which is 55.8 bushels per acre.

$$X_2=54.8,\quad X_3=1.7,\quad X_4=66.7$$

$$X_1=28.0756+3.0272(54.8)-$$
$$2.1556(1.7)-1.9487(66.7)=60.4$$

The proposed formula forecasts a yield of 4.2 bushels per acre above the actual 56.2 bushels per acre. The basic value of this corn yield versus soil temperature experiment is the establishment of quantitative relationships. One use of these relationships is in the early estimation of corn yield, but the size of the standard error of estimate ($s_{1.234}$=5.68 bushels per acre) should be kept in mind.

The 72-inch June 1954 soil temperature forecasts a 1954 yield of 58.9 bushels per acre. The 1-inch June 7 a. m. soil temperature forecasts about the same, 60.1 bushels per acre. A combination of both June parameters, which are available on the first of July indicates 59.5 bushels per acre. As this forecast is from June data and encompasses only normal change through the rest of the season, as based on the data of the preceding 16 years, some refinement may be achieved by using the Weather Bureau's 30-day outlook. For July 1954 central Iowa was placed in the transition zone from above to much above normal temperatures with subnormal rainfall. On this basis the forecast available July 1 of 59.5 bushels per acre would appear too high, and judgment reduction would be in order. On August 1, the 30-day outlook called for a change to above normal rainfall and subnormal temperature. On this basis and including the storage of excess heat from July, an August soil temperature of only slightly above normal could be assumed (about the same as the observed value) and the last "early" forecast issued using this information. The exceptionally accurate 30-day outlooks in 1954 made this corn yield forecast fairly accurate.

Let us now apply the formula to data for 1955. As mentioned earlier, prospects for a bumper crop early in July 1955 were considerably reduced by dry weather in late July and August. The actual yield was 54.3 bushels per acre.

$$X_2=55.4,\ X_3=2.6,\ X_4=70.0$$

$$X_1=28.0756+3.0272(55.4)-$$
$$2.1556(2.6)-1.9847(70.0)=53.7$$

The difference between the forecast and the actual yield for 1955 is very small, only 0.6 bushel per acre.

In 1956, a year that was dry throughout most of the growing season, the actual yield was only 51.6 bushels per acre. The formula forecast a yield of 58.4 bushels per acre, an overestimate of 6.8 bushels per acre.

$$X_2=55.1,\ X_3=3.2,\ X_4=66.5$$

$$X_1=28.0756+3.0272(55.1)-$$
$$2.1556(3.2)-1.9847(66.5)=58.4$$

5. CONCLUSIONS

Corn yield is related to the temperature of the soil and in Iowa reduced yields are associated with: (1) negative departures from the mean in May, with the relation strongest at 6 feet; (2) either negative or positive departures in June, with the relation strongest in the first 2 feet; (3) positive departures in August, with the relation strongest at 1 inch. The relation of soil temperature to corn yield is twofold: first, a direct influence on the development of the corn plant, and second, a measure of the effect of air temperature and moisture on the plant. During May, the relation of warm temperatures at 6 feet to high yield is indirect and is considered to be an indication of the earliness of the season. During June, the plant is small and the old Iowa adage, "knee high by the 4th of July," indicates a well-advanced stand; thus the relation of the 1-inch soil temperature in June is assumed to be direct. During August, the corn is 3 to 7 feet high, tall enough to shade the ground, and the relation is assumed to be more indirect than in June.

As described in section 3 soil temperature varies with different types of soil; therefore the mean temperatures, and their deviations from year to year as discussed in this paper, may not be applied to other soil temperature readings, even in the central division; also it should be borne in mind that these soil temperatures were obtained in fallow plots rather than in the field of corn. The Ames temperatures must be used as the standard for the central division and only after extended comparison with other readings could local refinement be achieved by using more local data.

The simplest case where a knowledge of soil temperatures may be put to use to increase corn yield is at planting time. If at that time, the 6-foot soil temperature is below normal and the outlook is for continued moist, cool weather, the corn yield prospect should be low. The temperature of the first few inches could be raised by ridge planting followed by shallow cultivation to aerate the ground, thus minimizing one of the worst threats to corn, a cold late spring.

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THE HURRICANE SEASON OF 1957

PAUL L. MOORE AND STAFF

Weather Bureau Office, Miami, Fla.

1. GENERAL SUMMARY

Eight tropical storms developed in the North Atlantic and Gulf of Mexico in 1957 and three of these reached hurricane force. The normal for recent years is 10 storms with about 5 developing into hurricanes. The pattern of movement (see fig. 1) was similar to that of 1956 with storms striking the Gulf coast but sparing the eastern seaboard as those in the Atlantic recurved offshore. Hurricane Audrey, which struck near the Louisiana-Texas border in June, was one of the most destructive June hurricanes of record and the first to occur in that month since 1945. The other two hurricanes, Carrie and Frieda, remained at sea in the Atlantic. Carrie persisted as a hurricane for more than two weeks and was responsible for the sinking of a ship near the Azores with the loss of 80 lives. Frieda was of minor importance and reached hurricane force only a few hours before it began losing its tropical characteristics.

Including hurricane Audrey, five tropical storms reached the United States, all on the Gulf coast between eastern Texas and northwestern Florida. None affected other coastal areas of the Gulf of Mexico or the Caribbean and there were no landfalls along the entire eastern seaboard. Property damage approximated $152,500,000 for the United States; none occurred in other areas. Audrey left 390 known dead, including 263 identified and 127 unidentified. There were 192 persons reported missing many of whom may be among the 127 unidentified dead. The loss of life in Audrey was the greatest of any tropical storm in the United States since the New England hurricane of 1938 and emphasized the difficulty of insuring the carrying out of adequate safety precautions and evacuation, even with the most recent methods of tracking and early warnings.

2. INDIVIDUAL STORMS

Tropical Storm (unnamed), June 8–14.—Pressures were abnormally low over the southwestern Gulf of Mexico and Yucatan area on June 7 but lack of upper-air wind observations from Mexico made the amount of circulation uncertain. However, late on the 7th and early on the 8th it became evident that a tropical depression existed. It moved rather rapidly northeastward with some deepening but little organization and crossed the Florida coastline in Apalachee Bay during the early evening. Two ships, one about 150 to 200 miles southeast of the center and later another 100 to 150 miles west of the center, reported winds of 45 knots. However, over coastal areas all strong winds were on the east side of the storm. Exposed places along the coast from Sarasota to north of Cedar Keys, Fla., experienced winds of 40 m. p. h. or more and tides 2 to 3 feet above normal with some damage. The storm weakened as it moved inland but set off an active frontal wave after moving off the Georgia coast on the 9th. Late on the 9th when the storm became extratropical off the Atlantic coast, ship reports indicated winds up to 65 knots.

Exceptionally heavy rain attended passage of this storm, particularly in Suwannee and all adjacent counties; 48-hour amounts of nearly 15 inches at official stations and some unofficial amounts as high as 19 inches. There was considerable damage to field and truck crops, particularly to tobacco and watermelons. Between 100 and 200 families were evacuated near Perry, Fla. According to the Meteorologist in Charge at Jacksonville, at least nine tornadoes or damaging wind storms were reported in northeastern Florida on the afternoon and evening of the 8th and another tornado over Jekyll Island in southeastern Georgia. No deaths were reported from these tornadoes and the damage and injuries were small.

One small craft capsized in the Gulf of Mexico and five of the seven persons aboard were apparently drowned. Damage in northwestern Florida from sea and rainfall flooding from the mouth of the Suwannee River to Port St. Joe was estimated at $30,000 and damage from tidal action along the Florida west coast was about $10,000. Tornado damage is estimated at $12,000. Therefore, total damage from this tropical storm was around $52,000 and there were five deaths.

Hurricane Audrey, June 25–28.—Hurricane Audrey, which struck the Gulf coast near the Texas-Louisiana border on June 27 with devastating effect, first became well defined over the Bay of Campeche, in the southwestern Gulf of Mexico, on June 24. A weak easterly wave which moved into the area a day or two earlier, as evidenced by changes in the wind field across the western Caribbean and Yucatan and by increased shower activity, was probably instrumental in initiating the disturbance. Klein [7] has discussed the formation and behavior in relation to the mean circulation for the period. He found that it was possible, using the 5-day 700-mb. height anomaly patterns, to track a negative anomaly center associated with Audrey back to its appearance in the western Caribbean during the period June 11–15. Namias [11] has demonstrated the relation of hurricane genesis to areas of negative anomaly on such mean charts. Two

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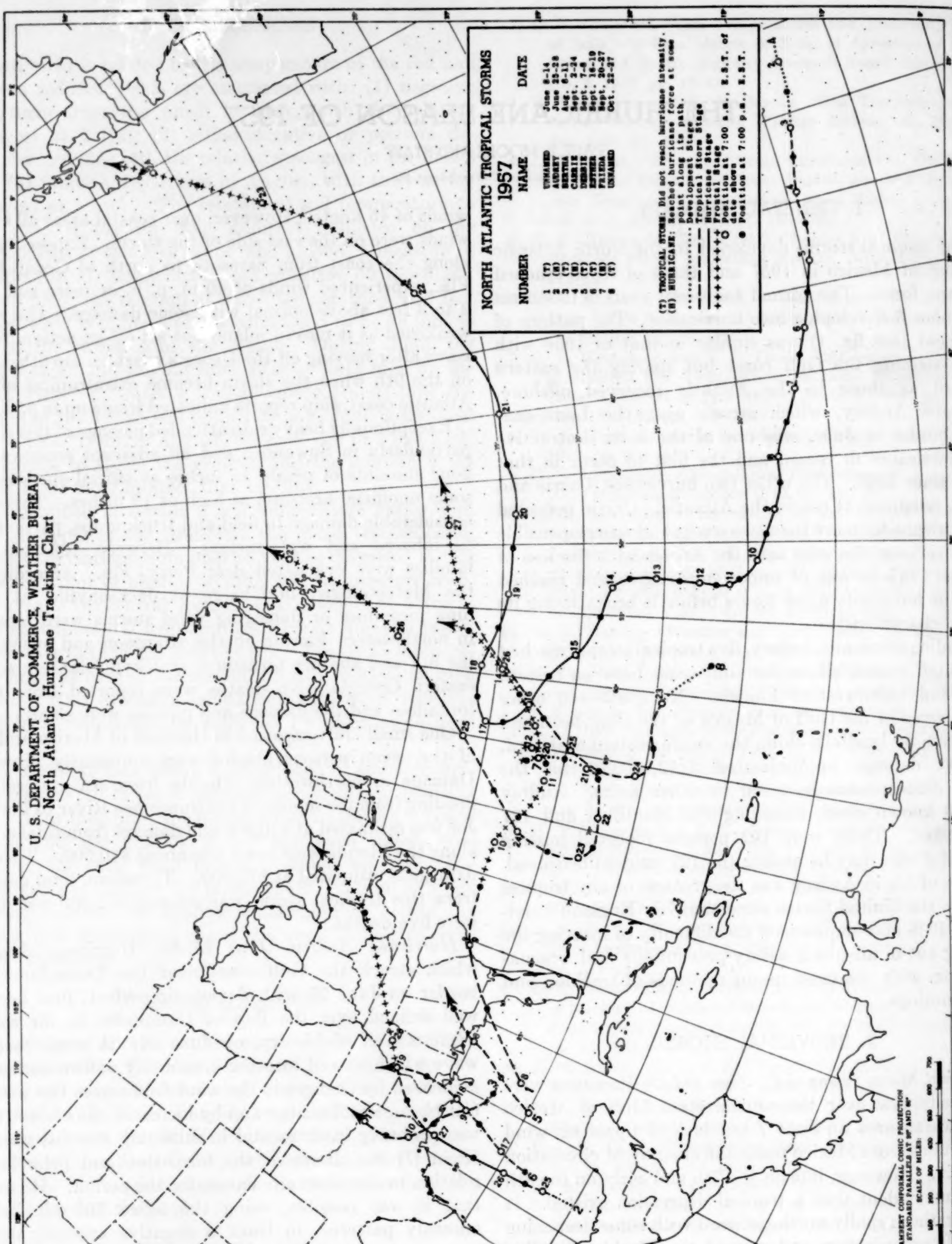

FIGURE 1.—Tracks of tropical storms and hurricanes of the 1957 season.

other factors recognized as important in hurricane formation—warm sea-surface temperatures and the proper divergent pattern at high levels—were present. While Klein used the techniques of the Extended Forecast Section of the Weather Bureau, applying 5-day or longer means to his analysis, the importance of some of the contributing factors is also apparent when viewed from a short-range aspect. For instance, the 200-mb. 5-day mean flow was shown to conform to the pattern suggested by Riehl [13] as conducive to deepening. The 200-mb. charts for the 25th to 27th show a marked intensification of the ridge over the middle and east Gulf, and, inferentially, of the high-level outflow from the storm area during this period.

The mean sea-surface temperatures for the Gulf of Mexico for June were generally 2° to 3° F. above normal. In addition, warming was evident preceding the development of Audrey with the highest temperatures (85° F.) in the area where the hurricane formed.

Audrey deepened during the night of June 24 while remaining nearly stationary. Aircraft reconnaissance on the morning of the 25th reported maximum winds of 85 knots and minimum pressure 989 mb. Although moderate to severe turbulence was encountered, radar presentation was characterized as "poor," a feature which usually indicates that a tropical storm is not as active or as "wet" as those with more definite rain bands. Rapid deepening would therefore not normally be expected. Late on the afternoon of the 25th a second flight reported that the maximum observed wind was 75 knots and the minimum pressure 979 mb. On June 26 both the size and intensity of the hurricane increased slightly. Reconnaissance showed maximum winds of 90 knots and a minimum pressure of 973 mb. A radar tracking flight during the night of the 26th reported the precipitation field as considerably more intense than observed 24 hours previously. However, no central pressure measurement was obtained. The only additional observation of central pressure prior to the landfall of the storm was that by the Tanker *Tillamook* near latitude 28.7° N., longitude 94.0° W. from 0910 to 1025 GMT, June 27. The minimum pressure observed was 969 mb. (The barometer was subsequently calibrated and the figure of 969 mb. is the corrected value.) Indications are that the ship was in the western portion of the eye and that the pressure observed was not the absolute minimum in the center at that time.

From June 26 until the center crossed the coast about 1430 GMT on the 27th, Audrey increased its forward speed from about 7 m. p. h. to 15 m. p. h. At the same time it intensified markedly. The central pressure when it struck the coast was some 30 mb. lower than that last reported by reconnaissance and there is no doubt that there was considerable deepening in the five hours between time of the observation of the *Tillamook* and landfall. The exact minimum pressure as the center reached the coast has not been determined. The Calcasieu Coast Guard station, 20 miles east of the center, reported 960 mb. and at Port Arthur, Tex., about an equal distance west of the center, the lowest pressure was 966 mb. The lowest pressure observed was 958 mb. by the Fish and Wildlife Service at Hackberry, La.

The Hydrometeorological Section of the Weather Bureau [9] has described the radial profile of sea level pressure of a model hurricane as:

$$\frac{p-p_0}{p_n-p_0}=e^{-R/r}$$

where p is the pressure at radius r, p_0 the central pressure, p_n the pressure to which the profile is asymptotic at some distance from the center and R the radius at which the wind speed is greatest. Because of sparse data and the lack of symmetry of the hurricane there is some leeway in values which can be assigned to the parameters in this case, particularly p_n and R. However, a minimum pressure of 938 mb. as computed from the formula, seems consistent with reports of wind, storm surge, and damage.[1]

Calculations using empirical formulae pertaining to maximum wind and storm surge and based on an estimated central pressure of about 940 mb. agree well with the data collected for the hurricane. A peak wind speed of 105 m. p. h. in a gust was read by eye from a wind dial at Sulphur, La., before the anemometer blew away. An oil rig reported winds up to 180 m. p. h. and a pressure of 925 mb. (It is not known whether this was a sustained wind or a gust, or whether it was measured or estimated.) Four sea tenders of the Continental Oil Company lost their anchors and were adrift in the hurricane just a short distance southeast of the center. The anemometers with which these tenders were equipped (not calibrated following the hurricane), all indicated winds in excess of 100 m. p. h. The three nearest the center indicated winds of 140 to 150 m. p. h. (These were peak gusts rather than sustained speeds and were read by eye from the anemometer dial indicators. The anemometers were 65 ft. above water.) Fletcher [3] has presented an empirical formula for calculating maximum winds in a topical storm. The formula, which is of the same form as those developed by Takahasi [15] and Myers [9], uses the difference between central and environmental pressure as a parameter. Fletcher's formula, which according to Myers [10] gives gust and not sustained speed, has proven very reliable in operational use when the central pressure was known. If this formula is applied, using the central pressure now believed to have existed in Audrey, the indicated maximum wind is about 150 m. p. h. While this is in agreement with several unofficial reports of extreme winds, the exact speed which occurred must remain in doubt.

As is usual in hurricane catastrophies, the most damaging feature was not the wind but its indirect effects through the storm surge. Nearly all the deaths can be attributed

[1] A manuscript by Hudson [5] has since come to our attention. In this, with the methods outlined in [9], the most likely value of central pressure was calculated to be approximately 946 mb. with a 70 percent probability that the true value was between 914 mb. and 958 mb.

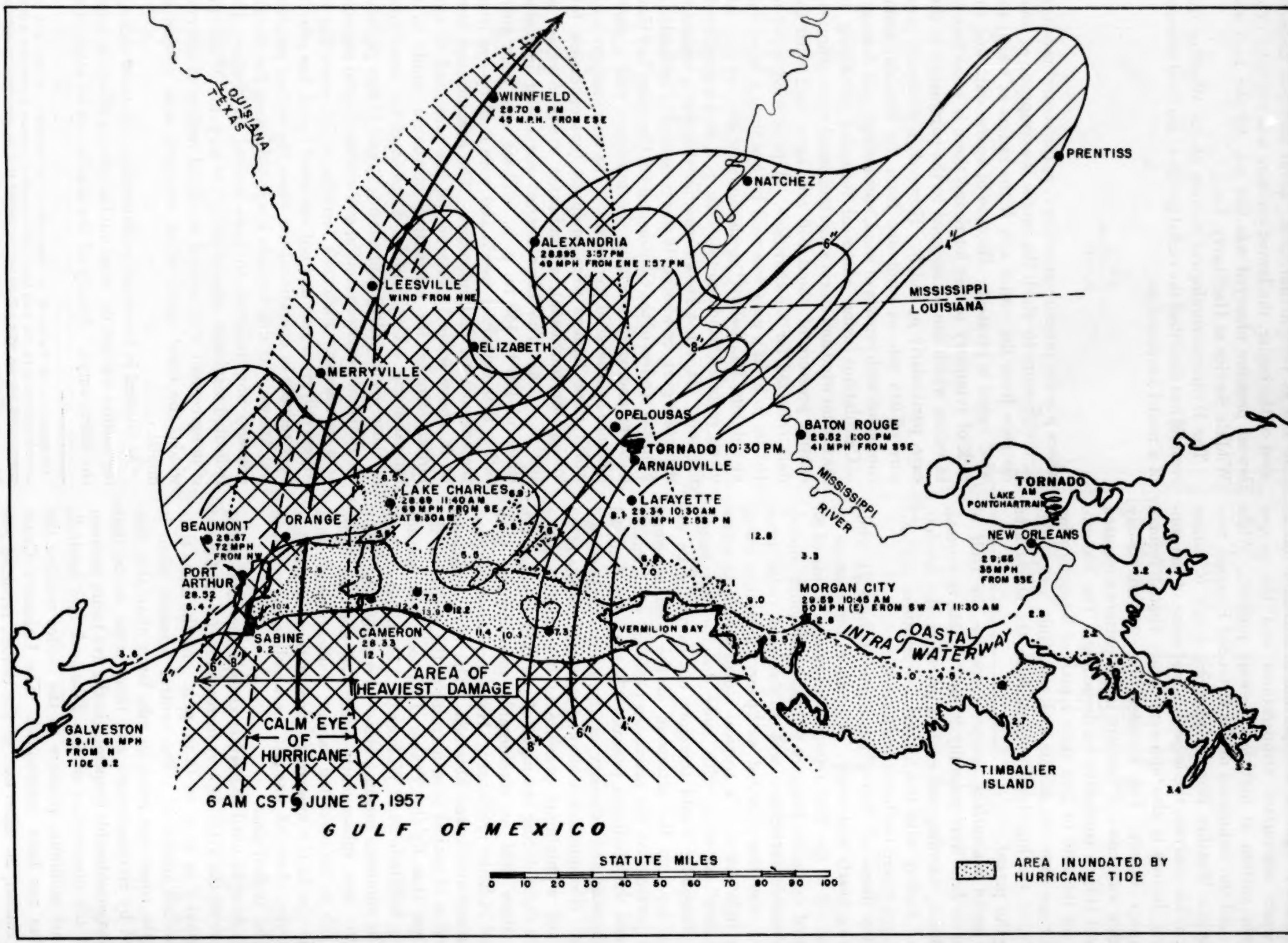

FIGURE 2.—Map showing landfall and track of hurricane Audrey in Louisiana on June 27. Windspeeds given are the fastest mile or the highest 1-minute speed; (E) = estimated. Pressure (inches) is the lowest observed at the point plotted. Tide heights are in feet above mean sea level, and were measured by the Corps of Engineers.

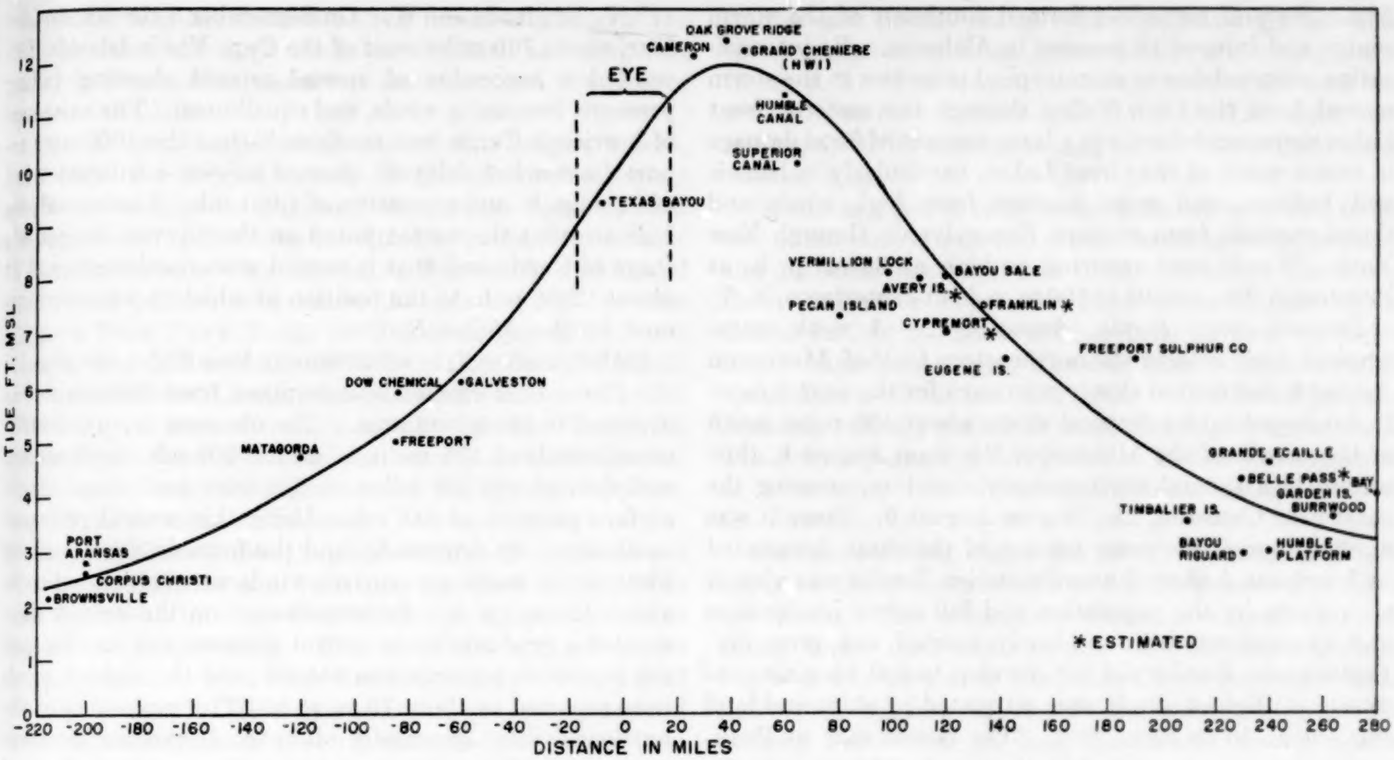

FIGURE 3.—Maximum tide heights recorded during the passage of hurricane Audrey.

to drowning by high tides. (See figs. 2 and 3.) Tides were reported to be more than 12 feet above mean sea level in Louisiana from the Coast Guard Station at Calcasieu Pass to Grand Cheniere, a distance of 24 miles.[2] Storm surge forecasts are extremely difficult and beset with many complicating factors other than meteorological, such as funnelling by coastal configuration or in bays, slope of the continental shelf, and the astronomical tide stage. A formula has been developed by Conner, Kraft, and Harris [1] for computing the probable height of the storm surge as a function of central pressure. Using 940 mb. as the minimum pressure, the formula indicates about 12 feet as the probable height. There is a vital difference between this value and the forecast of 7.5 feet which would be obtained using the 973-mb. central pressure last reported before the storm struck the coast. The capacity of the hurricane to generate a deadly storm surge was greatly increased by the rapid deepening just prior to landfall.

While it is not now possible to explain the rapid deepening or to suggest how it might be anticipated in the future, two possibly significant factors may be suggested. On June 26, rises in the 200-mb. heights over the storm area accentuated the high-level pattern indicated by Riehl [13] and Miller [8] as favorable to intensification. (A computation made on that date, using the procedure suggested by Miller, indicated 936 mb. as the potential depth of the hurricane.) Sea surface temperatures, recognized as an important factor in development of tropical storms, were abnormally warm and increasing. It also seems possible that sea surface temperatures near the coast may have been even higher than those generally indicated by ship reports over the Gulf, since very shallow waters extend a considerable distance from shore in this particular area.

In its later stages, the interaction of Audrey with the westerlies also created some forecast problems. As in some other notable hurricanes of recent years, strong baroclinic developments accompanying this interaction coincided with, and probably contributed to, radical readjustment of the broad-scale pattern. Since this, as well as the entire synoptic history of Audrey, is covered in a recent article by Ross and Blum [14], it will not be discussed here.

The exact number of deaths from Audrey will probably never be known. The list of known dead includes 371 in and near Cameron and 19 in other areas. To this list must be added a large number of others presumed dead from the 192 still listed as missing, although many of these may be among the 127 unidentified dead. The loss of life was the greatest in the United States since the New England hurricane of 1938 and about equal to the total for all other tropical storms in the United States in the past decade.

Property damage in Audrey is estimated at $150,000,000. In the Cameron to Grand Cheniere area, 60 to 80 percent of the houses were destroyed or floated off their foundations. Inundation extended inland as much as 25 miles over the low-lying area (see fig. 2). As the hurricane moved northeastward from Louisiana, it gradually weakened and began losing its tropical characteristics but was still attended by some damaging winds on the

[2] A high water mark found on Oak Grove Ridge, just north of the mouth of the Mermentau River, was subsequently established as 13.9 ft. m. s. l. by Corps of Engineers.

28th. Several tornadoes formed southeast of the storm center and injured 14 persons in Alabama. Re-intensification occurred due to extratropical processes as the storm moved from the Ohio Valley through the eastern Great Lakes region and there was a large amount of flood damage in States south of the Great Lakes, particularly in Illinois and Indiana, and some damage from high winds and thundersqualls from western Pennsylvania through New York. Winds were reported as high as 65 m. p. h. at Pittsburgh, Pa., and 95 to 100 m. p. h. at Jamestown, N. Y.

Tropical Storm Bertha, August 8–11.—A weak extratropical Low entered the northeastern Gulf of Mexico on August 6 and drifted slowly westward for the next 2 days. It developed into a tropical storm about 100 miles south of the mouth of the Mississippi River on August 8, then moved in a general northwesterly direction, crossing the coast near Cameron, La., late on August 9. Since it was moving toward the same portion of the coast devastated by hurricane Audrey 2 months earlier, Bertha was viewed with alarm by the population and full safety precautions and evacuations were evidently carried out promptly. Fortunately, Bertha did not develop to full hurricane intensity. Highest winds were estimated by ships and land stations at 50 to 70 m. p. h. The fastest mile at Beaumont, Tex., was measured at 44 m. p. h. with gusts to 52. Tides did not approach the disastrous proportions of those in Audrey, the highest reported being 4.7 feet at the west end of Vermilion Bay. The heaviest rainfall observed was 10.73 inches at Livingston, Tex.

The storm weakened and turned northward after moving inland, reaching southeastern Oklahoma on August 11. Although the storm was not identifiable as a surface circulation thereafter, it was apparent in the circulation aloft and in the accompanying heavy rains as it turned eastward across Arkansas. Two deaths resulting from Bertha were reported; property damage was slight, and the accompanying rain has been described by the Meteorologist in Charge at New Orleans Weather Bureau Office as over-all more beneficial than harmful.

The failure of Bertha to intensify similarly to Audrey may have been related to the broad-scale flow pattern. Green [4] has noted that in June, a strong trough prevailed in the 700-mb. mean pattern over the central United States, while in August this had been replaced by a strong High. The 200-mb. charts also indicate that the high-level outflow pattern was less favorable for deepening than in the case of Audrey.

Hurricane Carrie, September 2–24.—In early September the circulation pattern over the eastern Atlantic resembled that found by Namias and Dunn [12] to be characteristic of periods in which tropical storms develop in the Cape Verde area. The northeastward extension of the Azores High produced above-normal pressures in the area of western Europe while a trough prevailed near the west coast of Africa. Observations from the Cape Verdes on September 2 showed evidence of a vortex passing just to the south of the islands, and a message from Panair do Brasil reported a tropical storm developing near latitude 11° N., longitude 25° W. On September 6 the SS *African Star*, about 700 miles west of the Cape Verde Islands, forwarded a succession of special reports showing falling pressure, increasing winds, and squalliness. The existence of hurricane Carrie was confirmed when the 1600 GMT report (somewhat delayed) showed an east-northeast wind of 92 m. p. h. and a pressure of 1,001 mb. Later analyses indicate that the vortex noted on the 2d was the genesis stage of Carrie and that it moved west-northwestward at about 12 m. p. h. to the position at which it was encountered by the *African Star*.

On September 7, in an unusually long flight, the regular Air Force Gull reconnaissance plane from Bermuda was diverted to the storm area. The observer reported maximum winds of 138 m. p. h. at the 700-mb. level with a well-defined eye 20 miles in diameter and a minimum surface pressure of 945 mb. Using this central pressure, as obtained by dropsonde, and the formula developed by Fletcher [3], maximum surface winds were calculated to be about 130 m. p. h. Reconnaissance on the next 4 days showed a gradual rise in central pressure and on the 11th the minimum pressure was 984 mb. and the highest winds were reported as about 70 m. p. h. The weakening of the hurricane was apparently due to decreasing pressure gradient to the north as a low pressure trough formed across the subtropical High to a deepening Low near Newfoundland. This Low moved southward, reaching its most southerly position on the 11th, after which it began a slow retreat to the north. Carrie, having curved to a northerly course at this time, continued northward at 7 to 10 m. p. h. until September 14 when rebuilding of the high pressure ridge over the north Atlantic forced it to change course toward the northwest. This change in direction was accompanied by reintensification, and on the 12th reconnaissance aircraft found maximum winds of 108 m. p. h. and minimum sea level pressure of 960 mb. There were heavy wall clouds in all quadrants except the southwest. A continued increase in intensity and in size culminated on the 16th in what National Hurricane Research Project observers characterized as one of the most perfectly formed hurricanes they had seen. The winds of 138 m. p. h. reported on this date were the maximum surface winds observed during the life of Carrie but it is likely that higher wind speeds occurred during the period of lowest central pressure on September 7 and 8.

When the hurricane passed to the northeast of Bermuda on the 16th, poor radar definition and an increase in the diameter of the eye to 40 to 70 miles indicated weakening. However, as it curved eastward in advance of a trough moving into the North Atlantic, it still maintained maximum winds of near 100 m. p. h. for the next several days. On the 21st the German sailing ship *Pamir* encountered the storm southwest of the Azores and went down with the loss of 80 of her 86 crew members. Insufficient reports were obtained to indicate the maximum wind and lowest pressures observed as it passed through the Azores the next day but it is likely that winds of hurricane force persisted. Carrie began to assume extratropical features

thereafter and accelerated to the northeast, lashing the British Isles with high winds on the 24th and 25th and causing tremendous waves on the coast and floods over parts of the Isles.

Carrie was charted over one of the longest tracks, probably the longest track, of record—approximately 6,000 miles from its origin off the African coast to near Bermuda and back across the Atlantic to the British Isles. Formal advisories were issued from September 6 to 21 and additional advices were issued through the NSS bulletin (report from Navy Radio station at Annapolis) after it passed east of longitude 35° W. on that date. Aircraft reconnaissance of Carrie was of unusual quality. The Air Force flights from Bermuda on the 7th and 21st went farther east than any previous hurricane reconnaissance flight and the initial flight on the 7th covered approximately 3,700 miles with almost 17 hours in the air.

Tropical Storm Debbie, September 7–8.—On September 5 there was evidence of a weak easterly wave moving from the Caribbean into the Gulf of Mexico where a stagnant upper trough prevailed. This wave was apparently the trigger which set off a weak circulation in the central Gulf on September 7. This depression moved northeastward and only barely reached storm force before going inland near Fort Walton, Fla., about 40 miles east of Pensacola, on the morning of the 8th. Highest winds reported were around 40 m. p. h. at St. Marks. Tampa had gusts to 52 m. p. h. in a squall. The highest tide reported was some 150 miles east of the center on Apalachee Bay where it ranged from 2½ to 4 feet. Some flooding occurred due to the tides and rains, which were locally heavy, with 9.10 inches at Crawfordsville, Fla. There were no fatalities as a direct result of the storm although it was indirectly responsible for four deaths.

The failure of Debbie to intensify further may be attributable to two factors. The upper-air pattern never conformed to that found to favor intensification [8, 13]. In addition, there was evidence that cooler air entered the circulation as it moved near the coast.

Tropical Storm Esther, September 16–19.—Squalliness and abnormally low pressure in the southwestern Gulf of Mexico on September 15 indicated that a tropical depression might be forming. For about 2 days prior to this date a weak cyclonic circulation aloft had been drifting northwestward across Central America toward the Gulf. On the evening of the 15th the New Orleans Weather Bureau Office issued a bulletin announcing the development of a depression and forecasting intensification. Esther grew to storm intensity by late on the 16th and began moving northward at about 10 m. p. h. It never developed into a typical tropical storm with a small, well-defined eye but remained with a large area of relatively light winds roughly 100 miles across. This area passed inland on the southeastern Louisiana coast about daybreak on September 18, subsequently moving up the Mississippi Valley and weakening. As in the case of the first storm of the season (unnamed) and Debbie, much of the squalliness and high wind was a considerable distance to the east of the center. The highest reported wind speed was 52 m. p. h. at Pensacola airport, with gusts to 75 m. p. h. The lowest pressure observed on land was 1003 mb. at New Orleans and McComb, La., with 1000 mb. reported by reconnaissance aircraft before the storm reached land.

Squalls and heavy rains occurred in advance and to the east of the central area and continued along the Mississippi and Alabama coasts and near the mouth of the Mississippi River well after it passed. Five inches of rain fell at Buras, La., in 2½ hours with a total of over 13 inches there. Amounts ranging upwards from 6 inches through southeastern Louisiana and near the Mississippi and Alabama coasts resulted in some flooding in those areas. The property damage chargeable to Esther was estimated at $1,500,000 and three deaths were attributable to the storm.

Hurricane Frieda, September 20–27.—Hurricane Frieda spent its life at sea and was of hurricane force for only a few hours. The circulation which developed into this storm began on September 20. A cold front pushing southward to the rear of Hurricane Carrie passed Bermuda and a low center of 1010 mb., appearing at first to be nothing more than an incipient frontal wave, rapidly developed. Elsewhere, significant features were a 1020-mb. surface anticyclone some 700 miles to the north, and northerly winds of near 55 m. p. h. at 500 mb. and higher over the surface cyclone. By early morning of the 21st, strong easterly winds of 63 m. p. h. were observed at the gradient level at Bermuda. The LST *Narvik* reported the central pressure in the developing storm, about 400 miles south-southwest of Bermuda, as 1005 mb. Several factors favored intensification at this time. The strong low-level easterly winds north of the area resulted in a strong cyclonic shear, the sea surface temperatures were very warm, raobs from the *Narvik* and from Bermuda indicated that the cold front had dissipated, and there were favorable high-level winds for evacuation. By evening of the 21st, aircraft reconnaissance showed that central pressure had fallen to 1001 mb. and winds were up to 60 m. p. h. in squalls east of the center. Frieda was a reality. The movement was rather slow to the southwest.

Reconnaissance on the morning of September 22 found maximum winds of 50 to 60 m. p. h. in gusts with sustained winds generally 30 to 40 m. p. h. Shower activity was considerably less than normal and there was no extensive cloud shield. Meanwhile, upper winds at Bermuda were rapidly veering from northerly to southeasterly with decreasing speeds. This occurred as a high-level anticyclone northwest of the storm weakened and split in response to the approach of a short wave in the westerlies. This left the upper ridge with two cells, one over Florida and the other northeast of Bermuda.

With a less favorable circulation for intensification, Frieda showed little change through the 23d. At the same time, recurvature was favored by the new circulation pattern around the storm and it began to move toward

the northwest and north at about 10 m. p. h. during the night of the 23d. Simultaneously, as the short wave in the westerlies progressed eastward, the upper trough weakened and, perhaps in response to a more favorable high-level evacuation mechanism, the cloud systems began to show more organization and radar coverage became feasible for the first time. Forward velocity increased to 20 m. p. h. toward the north-northeast on the 24th and little change was observed in surface pressures. However, by morning of the 25th, the Canadian merchant ship *Irvingbrook* reported a barometer reading of 992 mb. and 80-m. p. h. winds. Frieda now was a hurricane—but only for a few hours for the cold front associated with the short wave mentioned previously was dropping into her circulation. Some further decrease in central pressure occurred as shown by a report from the ship *African Lightning*, giving a pressure of 978 mb. However, this was interpreted as the result of extratropical deepening since the storm was spreading out and there was no observed wind speed such as the 115 m. p. h. that Fletcher's [3] formula would indicate under true tropical conditions with such a pressure.

Although Frieda began under conditions not clearly tropical and became extratropical shortly after reaching hurricane force, soundings taken in the storm averaged slightly warmer than the mean tropical atmosphere. Aircraft data and surface pressures also showed good agreement with the relation given by Jordan [6] for tropical cyclones. However, throughout the life of the storm, the favorable parameters for hurricane formation and maintenance seem never to have operated concurrently or for long enough periods to produce a typical hurricane. After becoming extratropical, Frieda continued rapidly northeastward, with gradually decreasing intensity, and passed across Newfoundland on the night of the 26th.

No deaths or property losses have been charged to this storm.

Tropical Storm (*unnamed*), *October 22–27*.—On October 22 and 23, shower activity increased and pressures began falling near and to the north of the Lesser Antilles. A strong upper trough extended from the vicinity of Bermuda to Puerto Rico and on October 23 a small cut-off Low developed in this trough. The surface circulation increased markedly on this date, and in the evening a ship near the center of the circulation at about latitude 25° N., longitude 63° W., reported a barometer of 999 mb. and winds up to 35 m. p. h. On the 24th reports showed that there had been further intensification with winds in squalls up to 50 to 60 m. p. h. just north of the center and winds of 30 to 35 m. p. h. prevailing 200 to 400 miles from the center. The storm gradually curved from a northwesterly to a northerly direction at 12 to 15 m. p. h. The lowest surface pressure reported was 993 mb. by a ship near 28° N., 65° W. at 0600 GMT on the 25th. A gradual weakening and filling began thereafter with acceleration to the northeast. When the storm passed just east of Bermuda on the evening of October 25, there were strong winds east of the center but only moderate winds to the west in the area of Bermuda, the pressure gradient there having been weakened by the approach of an extratropical system which gradually absorbed the remnants by the 27th. This storm never developed many of the characteristics of a true tropical cyclone and in many respects was similar to tropical storms Dora and Ethel of 1956 and a quasi-tropical Low of October 1956 [2]. It caused no deaths or property damage.

ACKNOWLEDGMENT

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THE WEATHER AND CIRCULATION OF DECEMBER 1957 [1]

High Index and Abnormal Warmth

CARLOS R. DUNN

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

1. CIRCULATION OF THE MONTH—FAST WESTERLY FLOW

The monthly mean circulation pattern at 700 mb. for December 1957 (fig. 1) was characterized by fast westerly flow of small amplitude, typical of high index. The monthly mean zonal index for temperate latitudes (35°–55° N.), averaged over the Western Hemisphere, was 12.7 m. p. s. and exceeded the normal for December by 1.4 m. p. s. Not only were the westerlies fast, but they were also displaced to the north. The zonal wind speed profile for this month (fig. 2) shows that the latitude of the peak speed was north of its normal position and that the maximum wind was stronger than normal. In fact, zonal wind speeds were above normal from 40° N. to 70° N. (stippled).

Typical of high index, the 700-mb. mean waves (fig. 1) had small amplitude. Rather flat troughs were observed over Japan, the eastern Pacific, eastern North America, the Mediterranean region, and western Siberia. The Siberian trough, with a departure from normal of −540 feet, was by far the strongest, and although the maximum anomaly was in the north, subnormal heights extended southward through middle latitudes into the subtropics. However, this was not true of most of the other troughs which were relatively weak and did not extend strongly into lower latitudes. The 700-mb. heights in the Asiatic coastal trough averaged above normal in most latitudes. The eastern Pacific trough was deep in the Gulf of Alaska but weak in middle latitudes, where positive anomalies extended zonally through the trough. Likewise, the North American trough was not particularly pronounced, for heights in the trough were less than 100 feet below normal.

The ridge over the western United States and the accompanying trough over the Mississippi Valley may have been a result of the influence of the earth's orography on the fast westerlies. The average position of the trough (90°–95° W. longitude) was close to the location given by Colson [2] for trough formation to the lee of the Rocky Mountains, with wind speeds of the magnitude observed.

Positive height anomalies, associated with the fast westerly flow and the small-amplitude waves at 700 mb., were zonally oriented and mainly confined to middle and low latitudes, while the negative anomalies were located in the higher latitudes (fig. 1). The positive anomalies, which resulted from extensions of the subtropical Highs northward, were most pronounced in the central Pacific and Atlantic Oceans, where the normally cyclonic flow was replaced by anticyclonic flow and small-amplitude ridges in the monthly mean. The smaller positive anomalies over western United States and the below normal heights in the Gulf of Alaska and to the east over Canada reflect the high-index regime that existed in western North America, where difluence normally occurs.

Thus far only the average wind speed for the entire Western Hemisphere and its latitudinal variations have been discussed. Usually there are important longitudinal variations of wind speed which may be highlighted by an isotach chart. This month these variations were small, especially if Eurasia is excluded. At the 700-mb. level a band of wind speeds greater than 12 m. p. s. extended continuously from China to Great Britain (fig. 3A, hatched). Within this band centers of maximum speed did occur, but they were not strong and were located near their normal wintertime positions, off the eastern coasts of the continents.

Wind speeds were above normal not only along practically the entire jet stream axis but also to the north of this axis (fig. 3B). Largest positive anomalies were over the oceans, but the super-normal winds in western United States intensified orographic effects and, therefore, had a pronounced influence on the United States weather. South of the jet axis winds were weaker than normal, with the major negative anomalies located over the oceans in the subtropics, where large zones of above normal anticyclonic shear were observed.

Most features of the December circulation were well depicted by the midtropospheric circulation, but there was an additional aspect of the circulation which was best portrayed by the 200-mb. monthly mean. Even though the upper-level (200-mb.) contour pattern appeared very similar to that at lower levels, the wind field did differ significantly (fig. 4). At 200 mb. the jet stream maximum was located over Tennessee, some 1,500 miles southwest of the 700-mb. jet maximum off Nova Scotia. The relation of this wind field to precipitation will be discussed in section 5.

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[1] See Charts I–XVII following p. 424 for analyzed climatological data for the month.

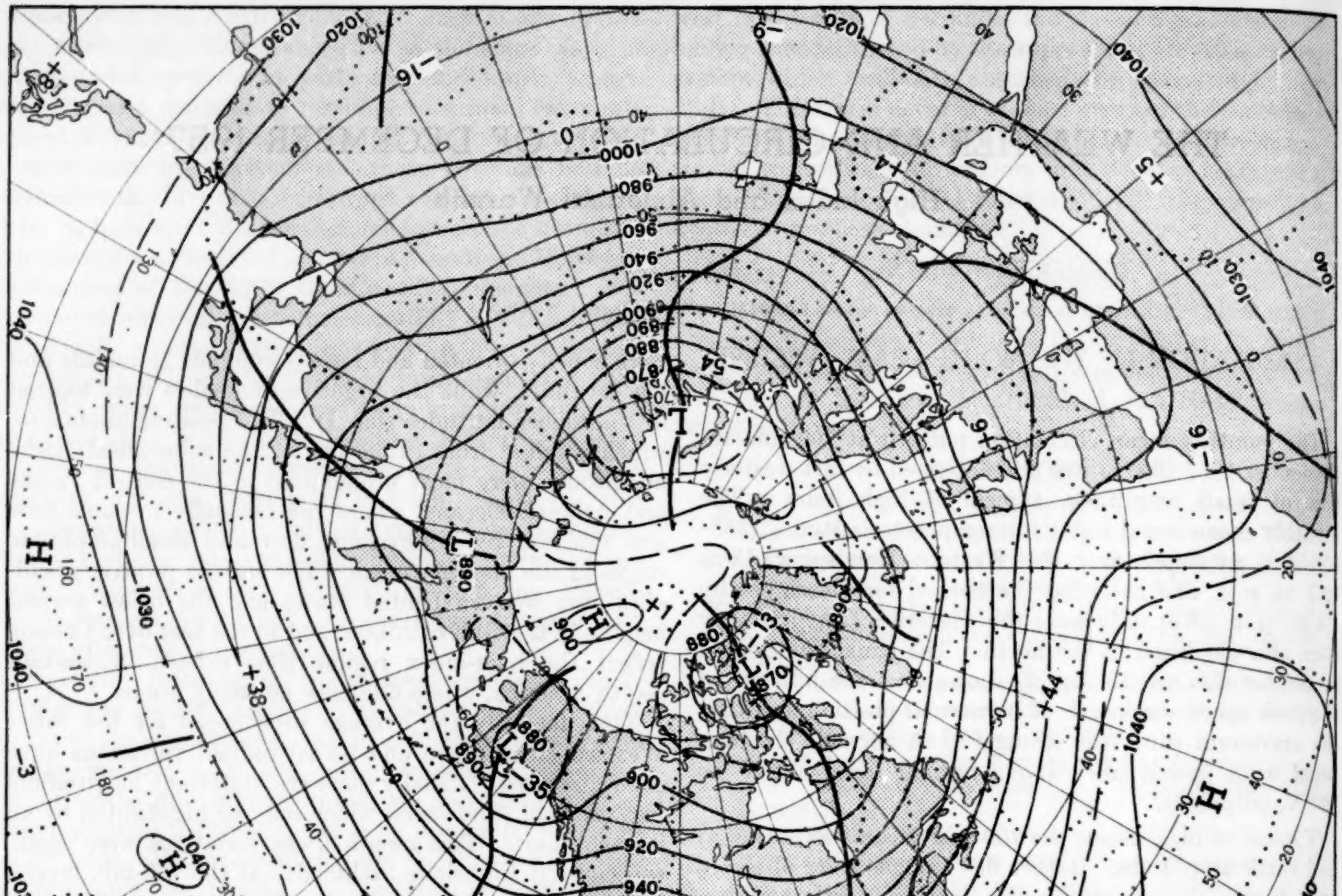

FIGURE 1.—Mean 700-mb. contours (solid) and height departures from monthly normal (dotted) (both in tens of feet) for December 1957. Fast, westerly, small-amplitude flow, typical of high index, prevailed this month.

2. CHANGE IN CIRCULATION FROM FALL TO DECEMBER

The high index circulation of December represented a marked change from the persistent low index regime that had existed throughout the fall [7]. During the fall, when blocking conditions prevailed, the temperate zone (35°–55° N.) index averaged below normal every month (table 1). (These indices and all zonal winds referred to in this section are the average for just the western half of the Northern Hemisphere.) It was not until late in November that the westerlies began a steady climb to the above normal value for December.

A quick inspection of the mean zonal wind speed profiles for November through December suggests that rather large departures from normal existed, and that these anomalies

TABLE 1.—*Monthly mean values of the zonal index at 700 mb. (in meters per second) for the area 35° N.–55 N. and 5° W.–175° E.*

	1957	Normal	Departure from normal
September	7.2	7.8	−0.6
October	7.3	9.5	−2.2
November	9.1	10.5	−1.4
December	12.7	11.3	+1.4

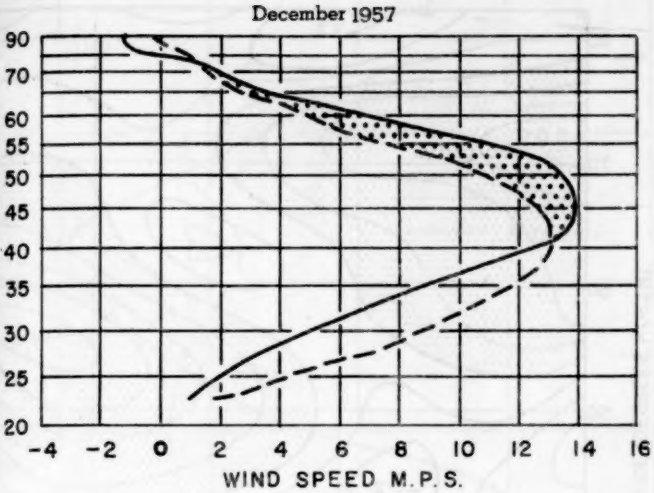

FIGURE 2.—Mean 700-mb. zonal wind speed profile in the Western Hemisphere for December 1957 (solid line) and December normal (dashed line). Westerlies were stronger than normal (stippled) and displaced to the north.

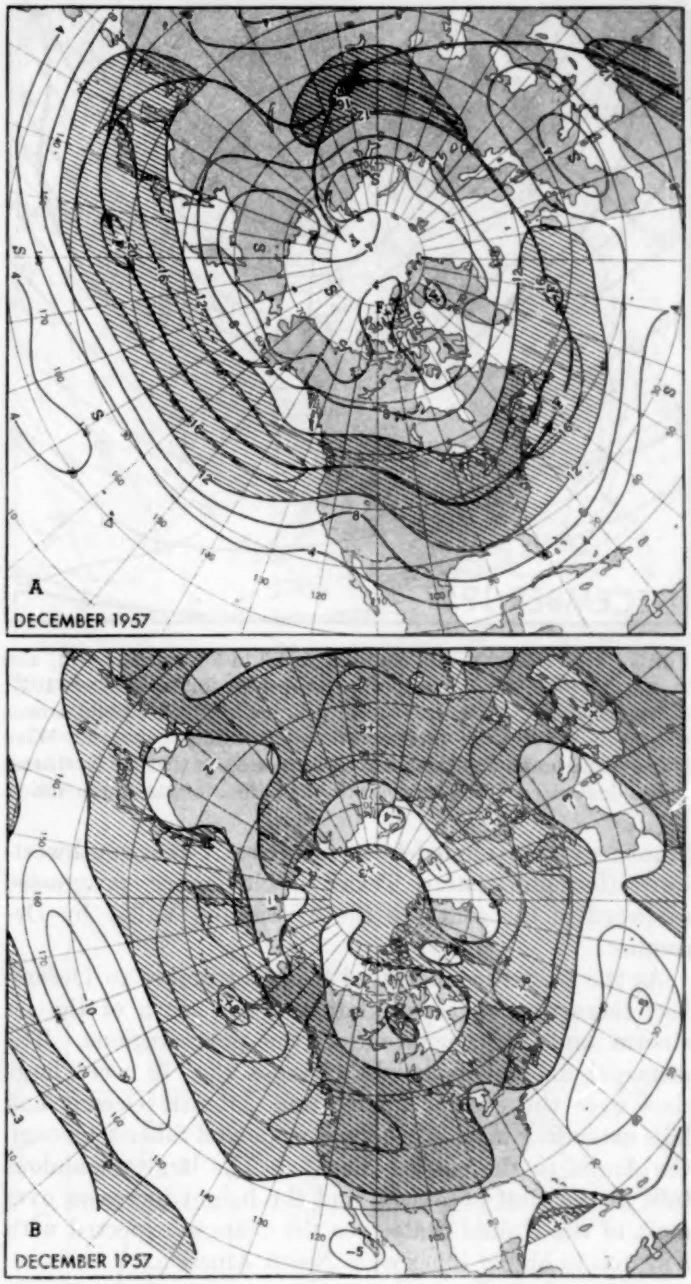

FIGURE 3.—(A) Mean 700-mb. isotachs and (B) departure from monthly normal wind speed (both in meters per second) for December 1957. Solid arrows in (A) indicate principal axes of maximum winds. Speeds greater than 12 m. p. s. have been hatched. Positive anomalies in (B) have been stippled. Faster than normal, zonally-oriented jet stream extended from China eastward to Great Britain.

seemed to undergo systematic long-period changes. In order to examine these ideas more carefully, zonal wind speed departures from the 30-day normals were computed twice a month for 5-degree latitude bands and plotted on a time-latitude section (fig. 5). As would be expected during the period of low index, from September through November, 30-day mean zonal wind speeds were subnormal in temperate latitudes but above normal in low and high latitudes. By the 30-day period mid-November through mid-December westerlies in the middle latitudes were above normal, and they continued to strengthen to over 4 m. p. s. above normal by December. Also, the positive departures, which were located in middle latitudes, migrated northward with time. They first appeared around latitude 50° N. in mid-November and later were centered at 57° N. in December. Simultaneous with the increase in zonal wind speed anomalies at middle latitudes, negative departures from normal at low latitudes increased in magnitude, reaching a maximum of 3.5 m. p. s. in December near 30° N.

The marked differences in the wind speed anomalies from November to December resulted from abnormal changes in the actual wind speeds. In order to illustrate this, the profiles of both the normal and 1957 changes were computed. The normal change is simply the normal zonal wind speed for December at a given latitude minus the corresponding normal value for November (fig. 6, dashed). The 1957 value is the monthly mean zonal wind speed for December minus the corresponding mean value for November (fig. 6, solid). It turns out that the normal changes in wind speed from November to December are minor north of latitude 50° N., but that they are large and positive south of that latitude with a maximum change of over + 3 m. p. s. between 30° and 35° N. This year, however, the wind speeds increased in the band from 36° N. to 63° N., with a major change in excess of + 4 m. p. s. between 50° and 55° N. While this increase occurred in the higher middle latitudes, the zonal winds actually diminished in the low latitudes, contrary to the normal situation.

While the wind field was thus changing from fall to December, there was a concomitant adjustment of the height field. The single trough in the central Pacific in November [11] was replaced by two troughs in December; one was located along the Asiatic coast and the other in the eastern Pacific (fig. 1). The trough in the United

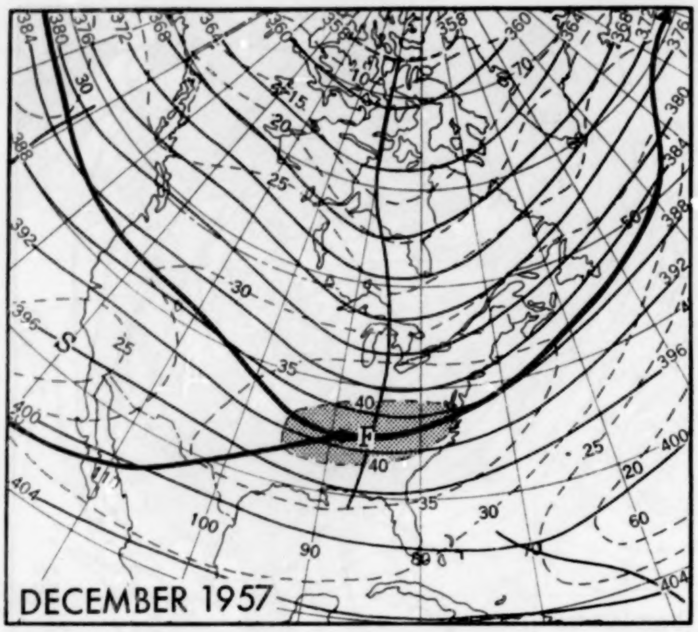

FIGURE 4.—Mean 200-mb. contours (solid in hundreds of feet) and isotachs (dashed in meters per second) for December 1957. Wind speeds greater than 40 m. p. s. are stippled. Solid arrows indicate the average position of the 200-mb. jet stream. Wind speed maximum was located over Tennessee, so that the Northeast was downstream from and north of the area of maximum winds.

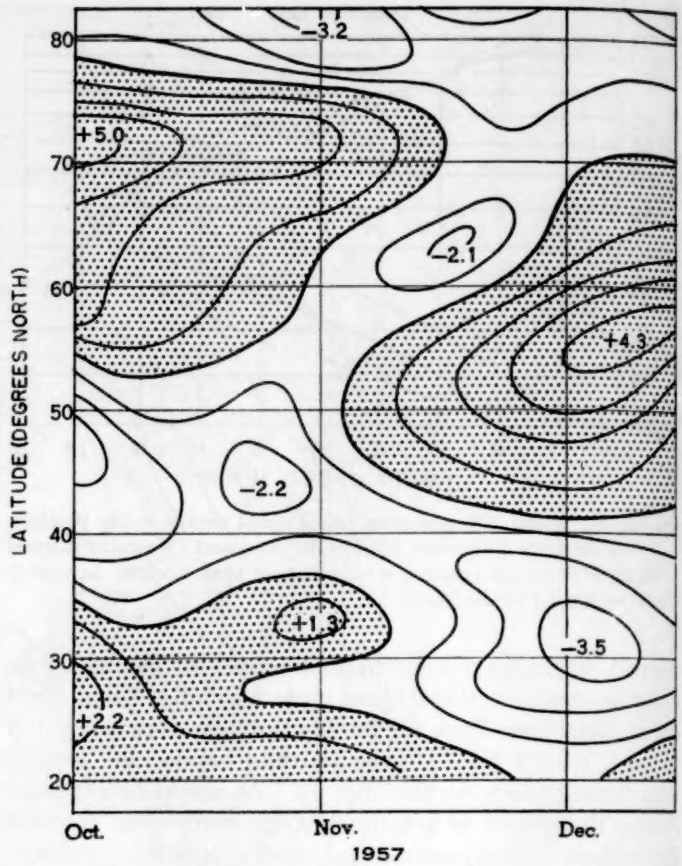

FIGURE 5.—Time variation of the departure from normal of monthly mean zonal wind speed (in meters per second), averaged over the Western Hemisphere. Isoline interval is 1 m. p. s. with anomaly centers labeled to the nearest tenth. Westerlies were stronger than normal in middle latitudes during December.

States, which extended from the Great Lakes southwestward through western Texas in November, progressed eastward in the south to the Mississippi Valley by December.

As the westerlies increased from November to December, there was an accumulation of air south of the jet stream and an evacuation in the polar regions. The principal anomalous height changes (fig. 7) were large rises over the central Pacific and Atlantic Oceans and falls extending from northern Europe and Siberia through the Arctic to the eastern Pacific. The large anomalous falls in the Gulf of Alaska and the height increases over most of the United States are the changes expected with a switch to higher index over North America.

3. TRANSITION WITHIN THE MONTH

The temperate zonal index as portrayed by the 5-day mean values (fig. 8) rose rapidly from subnormal values in November to rather high and persistently above normal values in December. The sharpest upswing occurred during the last week in November. After a period of high indices, a reduction in the westerlies occurred near mid-December. It was associated with the only large-amplitude flow pattern that occurred during the month over North America. The index fell rapidly again in the last 10 days of the month, as colder winter weather spread over the East.

The time variation of the latitudinal wind profile, again depicted by 5-day mean values (fig. 9), indicates the northward shift of the peak westerlies during the first half of December and the subsequent southward displacement, the more normal movement for this time of year. Apparently, the long-period northward shift of the westerlies terminated about mid-December. The weakening of the zonal flow is again in evidence just before midmonth, when the peak of the westerlies was farthest north and when the decrease in index took place.

Most of the 700-mb. 5-day mean charts during December (not shown) had small-amplitude waves over North America. The exception occurred in the second week, December 8–14, when a pronounced ridge in the West and sharp trough in the East were observed. The large-amplitude mean waves first appeared in the Pacific, then the meridional flow propagated rapidly downstream, modifying the waves over the United States and the Atlantic. It appeared to be a classical example of the dispersion of energy. During the rest of December the 5-day mean flow remained flat and there was a strong tendency for the same patterns to recur. Lee-troughs repeatedly formed over the Great Plains in response to the fast westerly flow and then moved eastward to the coast, but without any appreciable deepening.

4. ANTICYCLONE AND CYCLONE TRACKS

Because of the rather persistent regime of small-amplitude flow, the anticyclone and cyclone paths were

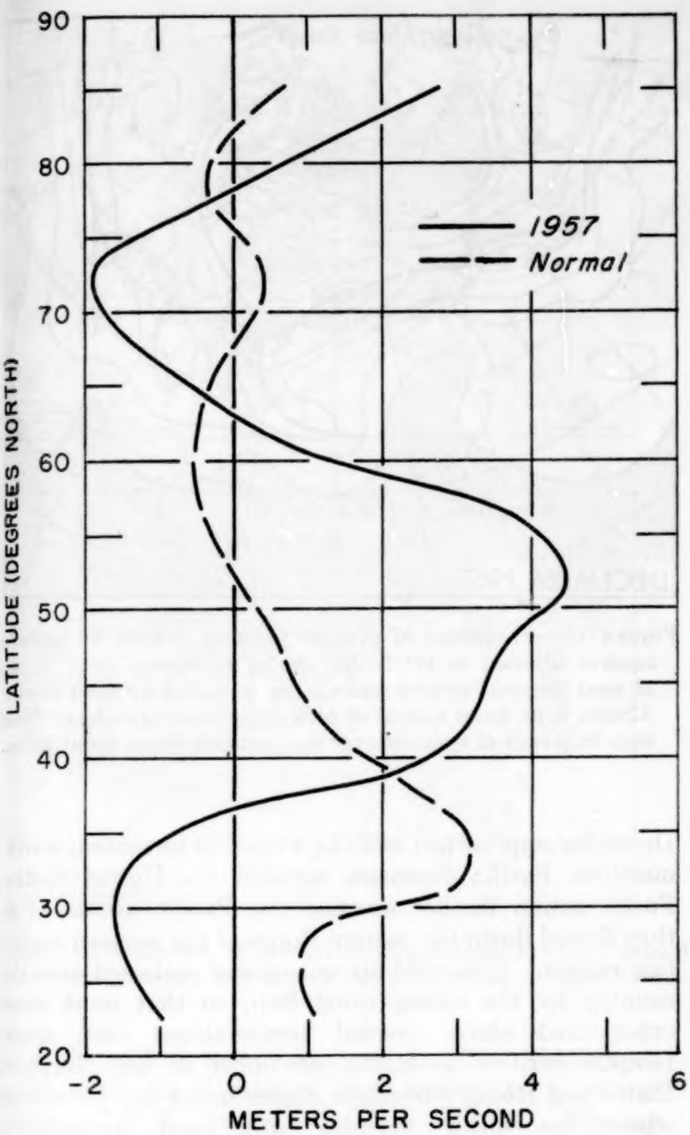

FIGURE 6.—Change in the monthly mean zonal wind speed averaged over the Western Hemisphere from November to December for 1957 (solid line) and for the normal (dashed line). Pronounced anomalous increase in westerlies occurred between 40° N. and 60° N. in December 1957.

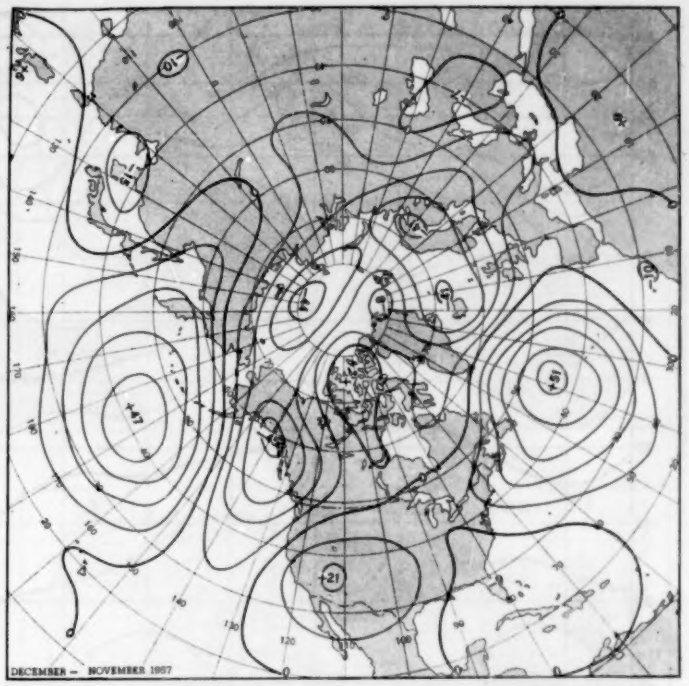

FIGURE 7.—Difference between monthly mean 700-mb. height anomaly for November and December 1957 (December minus November) in tens of feet. Isoline interval is 100 feet. Major anomalous height rises occurred in middle latitudes while falls were predominant in the higher latitudes.

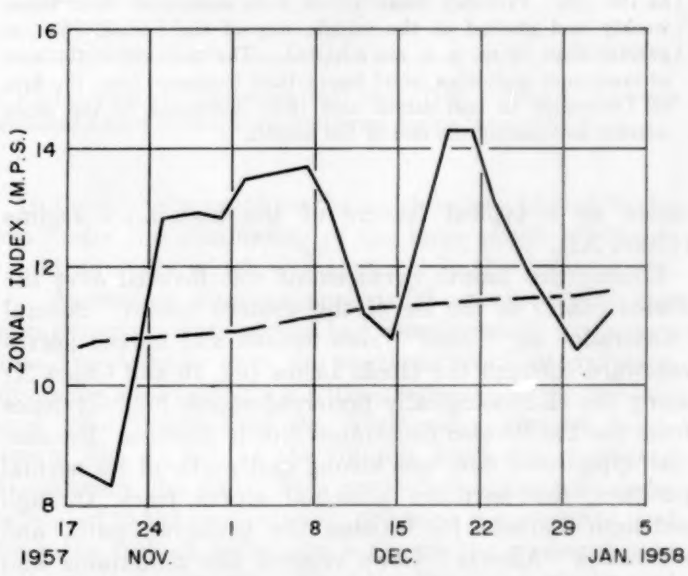

FIGURE 8.—Time variation of 700-mb. westerlies (in meters per second) over the Western Hemisphere for temperate belt (35°–55° N.). Solid line connects 5-day mean index values (plotted at middle of period and computed three times weekly) and dashed line shows variation of corresponding normal index. High index prevailed except for temporary weakening of westerlies near middle of month.

predominantly from west to east this December (Charts IX and X). There were no obvious preferred tracks of Highs over North America for they were almost uniformly distributed from the Gulf of Mexico to northern Canada. Only two polar Highs of Canadian origin had trajectories over the United States. One had only minor effects on United States weather as it grazed the northern Plains States and Great Lakes early in December, but the other produced a major polar outbreak in the second week, during the period of temporary weakening of the westerlies. This High, which formed in the Yukon on December 8, moved rapidly southward east of the Rockies to the Gulf of Mexico coast, producing a severe cold wave over the Southeast on December 12 and 13.

Most of the other Highs affecting the United States first appeared east of the Rocky Mountains as considerable anticyclogenesis occurred in the climatologically favored area over the Plains States [6]. Many of these Highs were break-offs from the Great Basin anticyclone which pre-

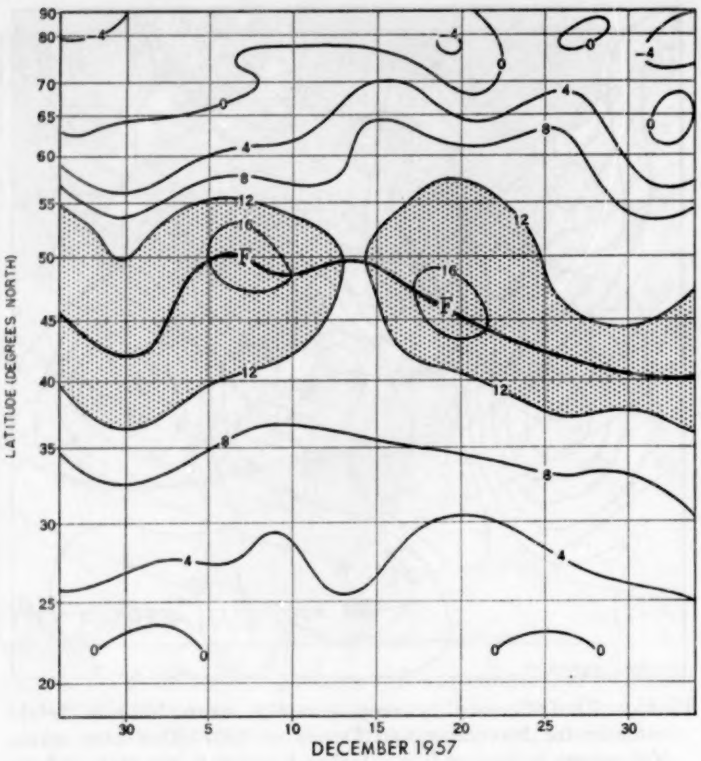

FIGURE 9.—Time-latitude section of 5-day mean zonal wind speeds (in meters per second) averaged over the Western Hemisphere at 700 mb. Five-day mean values were computed three times weekly and plotted at the middle day of the period. Values greater than 12 m. p. s. are stippled. The latitude of the axis of maximum westerlies (solid heavy line) increased from the first of December to mid-month and then decreased to the more normal location by the end of the month.

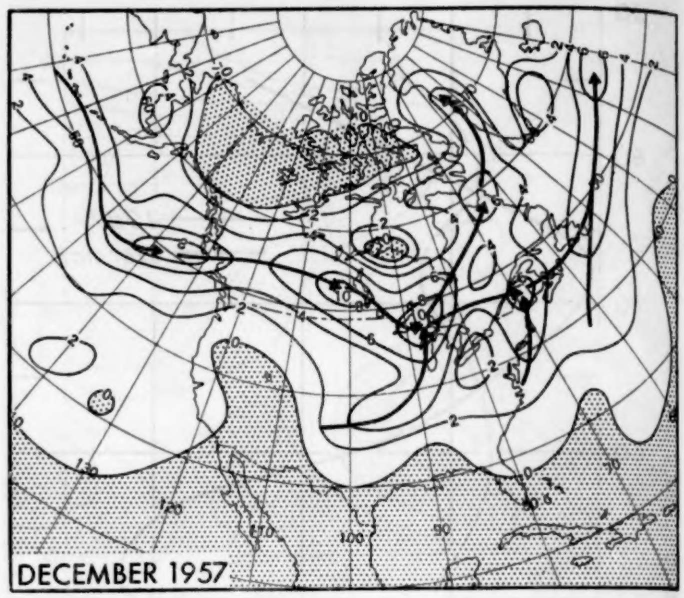

FIGURE 10.—Frequency of cyclone passages (within 5° latitude squares adjusted to 45° N. [6]) during December 1957. Zones of most frequent cyclone passage are indicated by solid arrows. Alberta type Lows typical of high index were prevalent. Note high frequency of cyclones over the relatively warm Great Lakes.

vailed as a typical feature of the high-index regime (Chart XI).

During this month cyclogenesis was favored over the Plains States in the lee of the western massif. Several "Colorado" or "Texas" Lows formed and moved northeastward through the Great Lakes (fig. 10 and Chart X) along the climatologically preferred course [6]. Cyclones from the Pacific also penetrated North America. Because the upper-level flow was strong and north of its normal position, the northern principal storm track through southern Canada [6] became the preferred path, and numerous "Alberta" Lows crossed the mountains and moved southeastward into the Great Lakes region. This preferred path, as well as many other features of this month, closely resembled December 1953, another high index month [12].

5. WEATHER OF THE UNITED STATES

TEMPERATURE—ABNORMAL WARMTH

December was an abnormally warm month, with its weather in many northern areas more typical of fall than winter. During the 3-month extended period of low index this fall, temperatures over most of the country averaged below normal [1, 4, 7, 10 No. 49, 11]. As December approached and the westerlies increased, warm, maritime Pacific airmasses invaded the United States. Foehn action further warmed the Pacific airmasses as they flowed down the eastern slopes of the western mountain ranges. This mild air was spread eastward over the country by the strong zonal flow, so that most areas experienced above normal temperatures each week. Largest positive anomalies prevailed in the Northern Plains and Rocky Mountain States under the jet stream where the foehn warming was most pronounced. 70 m. p. h. chinook winds were reported on the 7th and 10th at Rapid City, S. Dak., and this warm air reached as far east as Sioux City, Iowa, where 70 m. p. h. gusts and 63° temperatures were reported on the 10th. Several stations in the West including Havre and Glasgow, Mont., Sheridan, Wyo., Norfolk, Nebr., Raton, N. Mex., and Los Angeles and San Diego, Calif., reported the warmest December on record.

The areal extent of mild weather generally increased throughout December. During the third week only the southern half of Florida reported colder than normal weather (fig. 11), and in the fourth week only two small areas of subnormal temperatures in the far Southwest were observed. Further evidence of December's warmth was the fact that navigation did not end at Green Bay, Wis., until December 30, second latest date on record.

It has already been mentioned that the one major cold wave of December occurred during the second week when a polar airmass moved rapidly south-southeastward from western Canada to the Gulf. The maximum 63° F. temperature at Sioux City, Iowa, on the 10th, previously referred to, dropped to a minimum of 8° F. later that

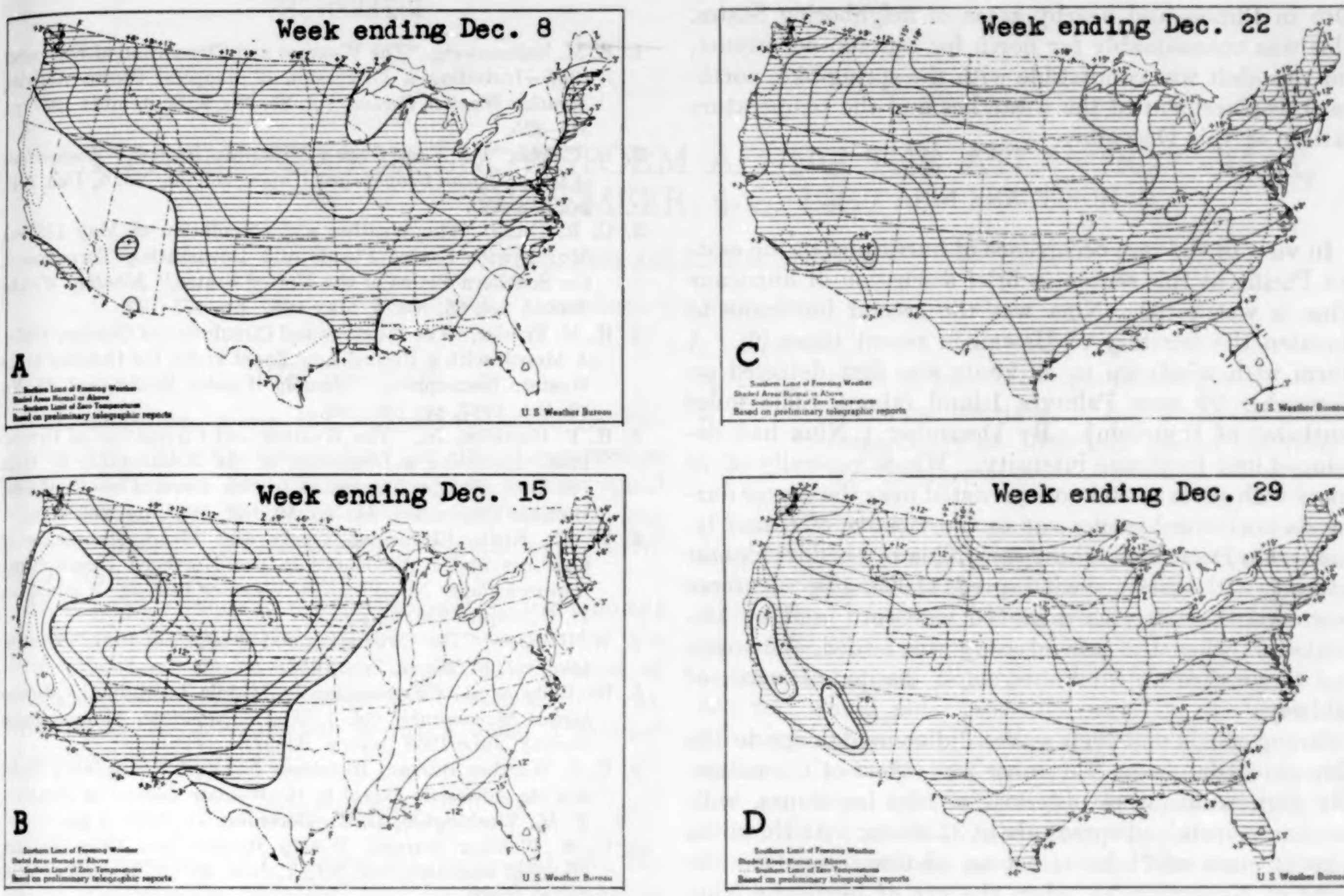

FIGURE 11.—Departure of average surface temperature from normal (°F.) for weeks in December 1957 (from [10]). Abnormally warm weather prevailed, especially in the Great Plains. One cold wave produced a hard freeze in the Southeast during the second week.

day as the cold air moved southward. This cold airmass settled over the Southeast, and weekly temperatures averaged 15° F. below normal in Florida. Freezing temperatures were reported from all areas east of the Rocky Mountains except for extreme southern Florida and Texas. In Florida, cold temperatures on the 12th and 13th approached those of the historic freezes of December 1934 and January 1940. The worst crop damage was confined to Florida and southern Texas. Damage to citrus groves is reported to be large, but the total extent will not be determinable for some time.

PRECIPITATION—TYPICAL OF HIGH INDEX

The December precipitation pattern (Chart II) was well related to the 700-mb. mean flow (fig. 1). Precipitation was generally widespread west of the Continental Divide but particularly intense along the Pacific coastal slopes, where the rainfall was enhanced by the orographic component of the strong westerlies. Up to 14 inches of precipitation fell in the extreme Northwest. Except for Minnesota, most areas of the Central and East Coast States, which were located under or east of the mean trough at 700 mb., received 2 or more inches of precipitation, but the above normal amounts were confined to the Northeast. Indianapolis, Ind., and Worcester, Mass., reported the wettest December on record.

In the lower troposphere the northeastern United States was under the domination of the large positive 700-mb. height anomaly which was centered in the Atlantic (fig. 1). Anomalous wind components [5] associated with this large departure from normal had a southeasterly trajectory from the Atlantic over the northeastern United States, producing a prevailingly maritime regime. At the 200-mb. level wind speeds over the Northeast decreased downstream (fig. 4), but at the 700-mb. level they increased downstream (fig. 3A). This particular configuration may be related to the precipitation, provided it is assumed that the mean isotach maximum indicates the preferred seat of the daily jet maxima. Since the Northeast was located north of the jet stream axis at 200 mb. and downstream from the jet maximum, it was in exactly the favorable area for upper-level divergence and precipitation according to Riehl [8]. The opposite variation of the wind speed in the lower troposphere, below the level of non-divergence, as indicated by the 700-mb. flow, favors convergence and precipitation. A similar relation was noted over the Great Plains in May 1957 [3].

In the lee of the Divide, over the Plain States, the rain shadow was pronounced. Raton, N. Mex., reported the driest December on record, and other small areas received no measurable precipitation during the month.

Numerous tornadoes were reported on the 18th and

19th in Illinois and nearby areas of neighboring States. This was unseasonably far north for tornado occurrence, but this shift was compatible with the spring-like, northward displacement of the westerlies and the temperature pattern of this December.

6. HURRICANE NINA

In view of the rare occurrence of hurricanes in the eastern Pacific at this season, a brief discussion of hurricane Nina is warranted. Nina was the second hurricane to threaten the territory of Hawaii in recent times [9]. A storm with winds up to 50 knots was first detected on November 29 near Palmyra Island (about 1,000 miles southeast of Honolulu). By December 1 Nina had developed into hurricane intensity. Winds generally of 70 knots with gusts to 90 knots persisted near the center during its northward movement to the vicinity of Kauai Island. On December 4, hurricane Nina reached its highest intensity with sustained wind speeds of 90 knots. Its force decreased thereafter as it moved westward, and by December 7, when the last advisory was issued, the winds had diminished to 30 knots, as it dissipated south of Midway.

Strong winds and high waves did some damage to the Hawaiian Islands on November 30. Most of the unusually high winds were observed on the lee slopes, with maximum sustained speeds about 35 knots. At Honolulu Airport gusts of 71 knots set an all-time record on the night of November 30, when the eye of hurricane Nina was located about 300 miles south-southwest of Honolulu.

Heavy rainfall of 20.42 inches occurred in a 14-hour period between about 8:00 a. m. and 10:50 p. m., December 1, at Wainiha on Kauai. Roads were washed out by floods from heavy rains, and homes were damaged by high waves on the coast of southern Kauai.

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AN EARLY-SEASON SNOWSTORM ALONG THE ATLANTIC COAST, DECEMBER 4–5, 1957

JOHN B. FUGE AND JOHN M. KIPPER, JR.

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

The snowstorm along the Atlantic Seaboard on December 4–5, 1957, was unusual only in that it occurred so early in the season, being in other respects only a typical winter nor'easter. However, the snowfall, over one foot in places, made it one of December's outstanding meteorological features.

An attempt is made to use Petterssen's [1] development equation in a qualitative manner to account for the development of the storm together with a method of estimating divergence proposed by Cressman [2]. An estimate of the precipitation is made using a method presented by Swayne [3].

2. DEVELOPMENT

The development of the storm is investigated with the aid of Petterssen's equation for the local change in vorticity at the surface $\partial\eta_0/\partial t$. The equation may be written, neglecting terms shown to have negligible contribution (cf. Means [4]):

$$\frac{\partial\eta_0}{\partial t}=A_\eta-\frac{g}{f}\nabla^2A_h-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\left(\overline{\omega(\Gamma_a-\Gamma)}+\frac{1}{c_p}\overline{\frac{dW}{dt}}\right)\right]$$

where:

A_η is the vorticity advection at the level of non-divergence.

$-\frac{g}{f}\nabla^2A_h$ is the development contribution of thickness advection for the layer 1000 mb. to the level of non-divergence; it is proportional to the Laplacian of thermal advection A_h for the layer. g is the acceleration of gravity and f is the Coriolis parameter.

$\overline{\omega(\Gamma_a-\Gamma)}$ is the stability, or "buoyancy" term, whose negative Laplacian represents the development contribution of local thickness changes due to adiabatic processes. $\omega\equiv dp/dt$, and Γ_a and Γ are respectively the adiabatic and actual lapse rates with respect to pressure.

$\frac{1}{c_p}\overline{\frac{dW}{dt}}$ is the mean rate of heating of the layer due to non-adiabatic processes. The negative Laplacian of this term therefore represents the development contribution of local thickness changes due to non-adiabatic processes.

c_p is the specific heat at constant pressure.

R is the gas constant, p_0 and p are the pressure respectively at 1000 mb. and at the level of non-divergence.

Since the terms were used only in a qualitative sense to determine their contribution to low-level convergence they were investigated separately even though they are not independent processes. For the same reason, after inspection of the relevant upper-level charts, it was felt that the assumption of an isobaric level of non-divergence at 500 mb. would not change the signs of the terms contributing appreciably to the vorticity tendency at the surface. It can be seen from the development equation that negative Laplacians of the thermal terms together with positive vorticity advection will give positive contributions to vorticity production and thus intensification at the surface.

To study the vorticity advection at the level of non-divergence ($A\eta$), the vorticity at 500 mb. was computed by using the finite difference method with a grid length of 200 km. The vorticity field was then superimposed on the 500-mb. contours and the vorticity advection was studied.

The Laplacian of thermal advection $-\frac{g}{f}\nabla^2A_h$ was studied by means of the 1000-500-mb. thickness charts. The field of advection was computed as the product of the geostrophic wind component and the thickness gradient measured over a distance of 100 nautical miles. Multiplication by a suitable factor gave the result as thermal advection in °C. per 12 hours. The field of thermal advection was then plotted and the Laplacian computed by finite differences over a 200-km. grid. To define the areas of positive or negative Laplacian, 25 to 40 points were used at each observation time.

The buoyancy term $-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\overline{\omega(\Gamma_a-\Gamma)}\right]$ and the term for the contribution of local thickness changes due to non-adiabatic processes, $-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\frac{1}{c_p}\overline{\frac{dW}{dt}}\right]$ were only qualitatively evaluated.

As vertical motion charts were not being routinely prepared by the Joint Numerical Weather Prediction (JNWP) Unit at this time, the sense of vertical motion was inferred from the divergence, which was qualitatively

estimated by using the method proposed by Cressman [2]. Essentially this utilizes the vorticity equation with certain assumptions[1] to obtain the equation

$$\nabla_H \cdot \mathbf{V} = \mathbf{V}_T - \nabla_H \ln \eta$$

where $\nabla_H \cdot \mathbf{V}$ is the horizontal divergence of the wind vector $\mathbf{V}$ at the level in question, $\mathbf{V}_T$ is the vector wind difference between the level of non-divergence and the level in question, and η is the absolute vorticity (vertical component) at the level where the divergence is desired. This logarithmic vorticity advection, which is inversely proportional to the size of the areas formed by intersections of thickness lines with vorticity lines at the level in question, was not actually computed. It was visually estimated from superimposing the thickness and vorticity charts. Thus, if the thermal wind blows from low to high vorticity at the lower level, divergence exists; or if the thermal wind blows from high to low vorticity, convergence exists.

This was correlated with the stability index charts and it was found that in general the maximum contribution of the stability term was in the areas of maximum warm air advection. This is, of course, to be expected since only in areas where the vorticity lines were not parallel to the contours would significant differences have occurred. While the pattern of the stability index (fig. 10) showed some change through the period, with less positive values following the developing surface system, the values did remain large and positive. Thus the buoyancy term would act as a brake over the land areas. Offshore it is likely that, with the aid of the non-adiabatic heating term, the stability could be negative and contribute to the development.

Indications that the entire development took place on the Arctic front were evident by near or below normal values of the departure from normal 1000–500-mb. thicknesses south of the front and eastward into the Atlantic during the period considered. This was the case not only in the upper part of the 1000–500-mb. layer, but was also apparent from inspection of the surface elements and the fact that the amounts of precipitation occurring in the Southeastern States during this period were not those associated with tropical air.

As for the synoptic events, earlier charts (not shown) showed that on December 2 a Pacific occlusion associated with a 500-mb. short-wave trough moved eastward into the Texas Panhandle where a wave became organized on the Arctic front that lay in an essentially east-west line along the 35th parallel. By 0000 GMT, December 4 (fig. 1) the wave had moved into Kentucky and deepened 5 mb. However, as can be seen from figure 4, the axis of maximum vorticity advection was already east and south of the surface Low, indicating the development over the center should be at a decreasing rate, especially if the favorable Laplacian of thermal advection over West Virginia (fig. 7) should be diminished. On the other

[1] Neglecting horizontal solenoids, friction, vertical transport of vorticity, and rotation of vorticity from about a horizontal to about a vertical axis.

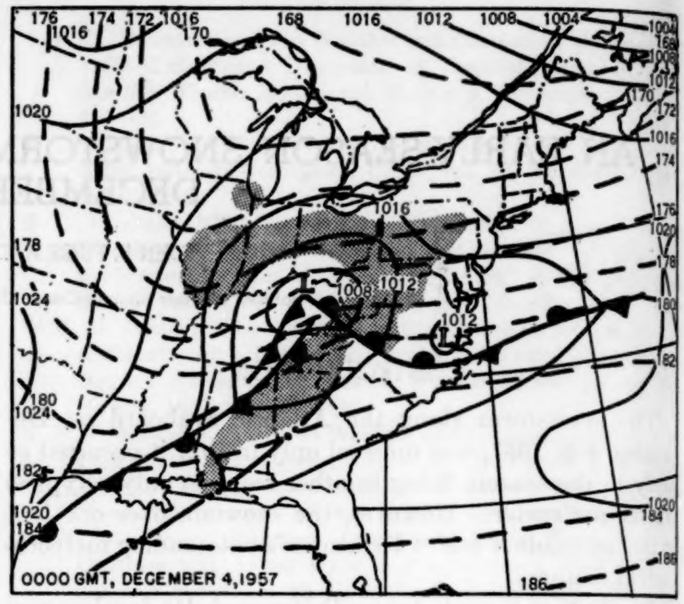

FIGURE 1.—Sea level chart for 0000 GMT, December 4, 1957, with 1000–500-mb. thickness (dashed lines). Shaded areas indicate current precipitation.

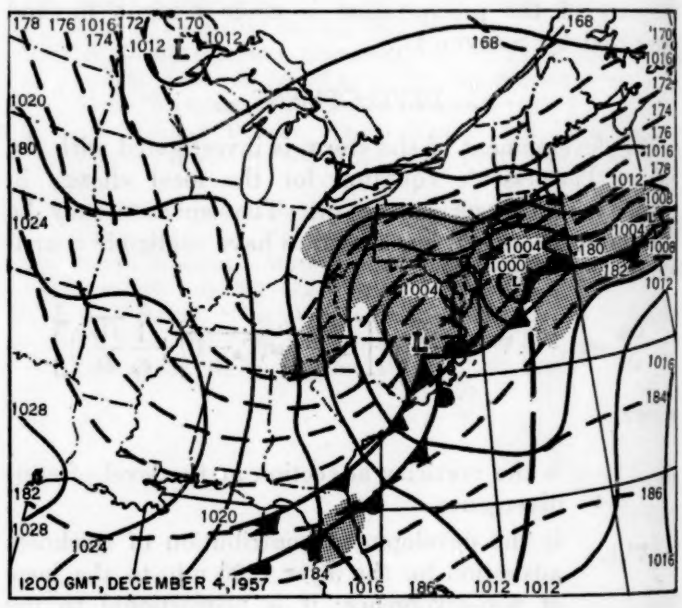

FIGURE 2.—Sea level chart for 1200 GMT, December 4, 1957, with 1000–500-mb. thickness (dashed lines). Shaded areas indicate current precipitation.

hand, along this axis of maximum vorticity advection from Pennsylvania to Alabama (fig. 4) there was a small area of much larger values in eastern Tennessee superimposed upon a near zero value of the Laplacian of thermal advection. According to Petterssen this should be a favored area for development, especially if there were any contributions from the other terms. Positive vorticity advection aloft, just east of Norfolk, was also favorable for intensification in that area. The lesser magnitude of the vorticity advection was probably compensated for by a strong contribution to vorticity from the non-adiabatic term as a result of heating from the underlying

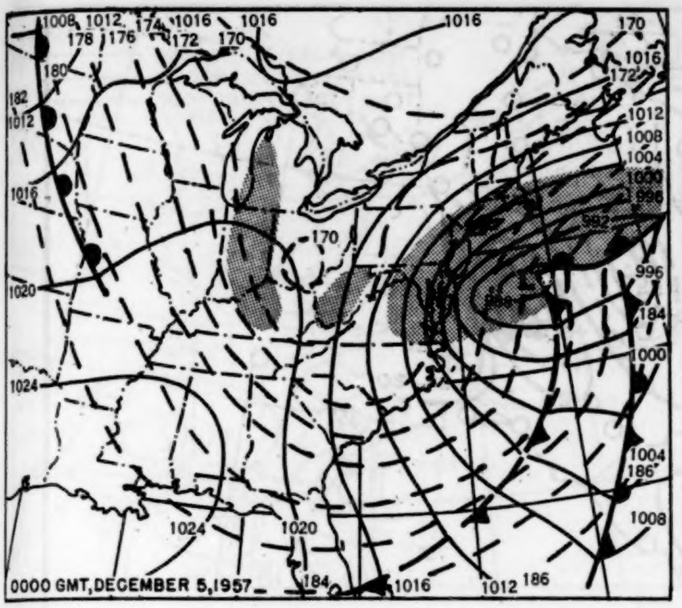

FIGURE 3.—Sea level chart for 0000 GMT, December 5, 1957, with 1000–500-mb. thickness (dashed lines). Shaded areas indicate current precipitation.

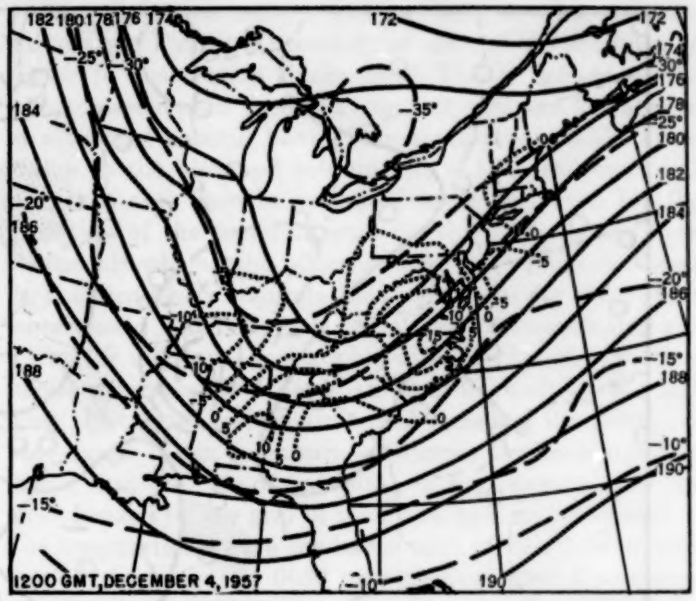

FIGURE 5.—500-mb. contours and isotherms (dashed lines) for 1200 GMT, December 4, 1957. Vorticity advection indicated by dotted lines in units 10^{-9} sec^{-2}.

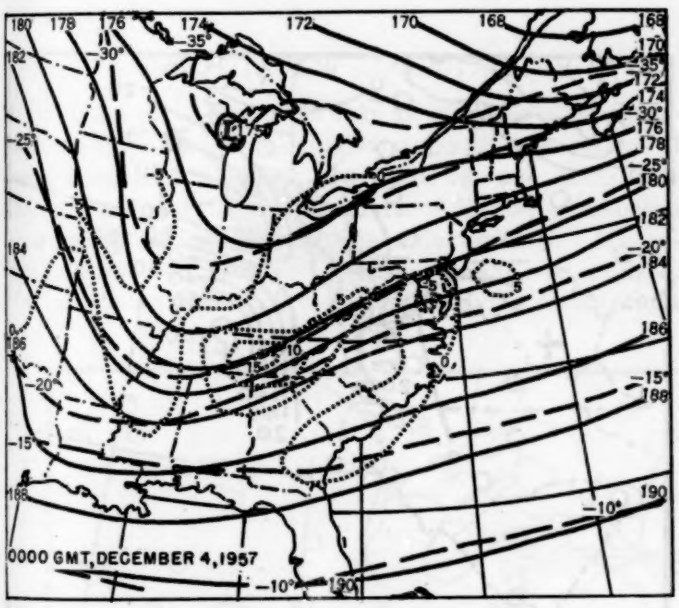

FIGURE 4.—500-mb. contours and isotherms (dashed lines) for 0000 GMT, December 4, 1957. Vorticity advection indicated by dotted lines in units 10^{-9} sec^{-2}.

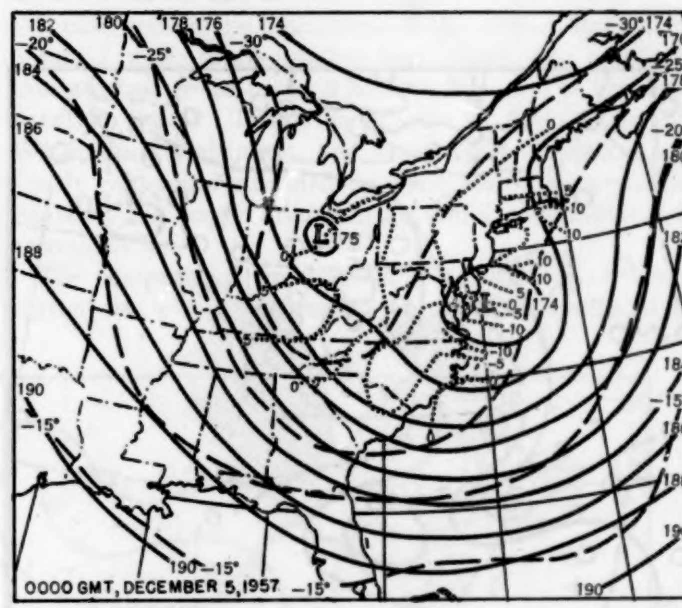

FIGURE 6.—500-mb. contours and isotherms (dashed lines) for 0000 GMT, December 5, 1957. Vorticity advection indicated by dotted lines in units 10^{-9} sec^{-2}.

sea surface. This heating effect would in turn react favorably on the stability term. Thus maximum intensification should occur on an axis from east of Norfolk through eastern Tennessee.

By 1200 GMT, December 4 (fig. 2) the maximum intensification did occur along that axis and two Lows, one in North Carolina and the other out to sea, developed and were both increasing in intensity. With no vorticity advection and rapidly decreasing temperature contributions, the original Low over Kentucky moved into eastern West Virginia and filled. Even with the area of maximum vorticity advection aloft directly overhead (fig. 5), indicating its maximum contribution had already been made, the Low in North Carolina continued to intensify as it moved offshore and received the contribution of non-adiabatic heating from the sea surface. The final map, 0000 GMT, December 5 (fig. 3), shows that the two Lows merged into a large east-west trough which was still increasing in intensity. With the Low aloft now much closer to the surface Low, the vorticity advection

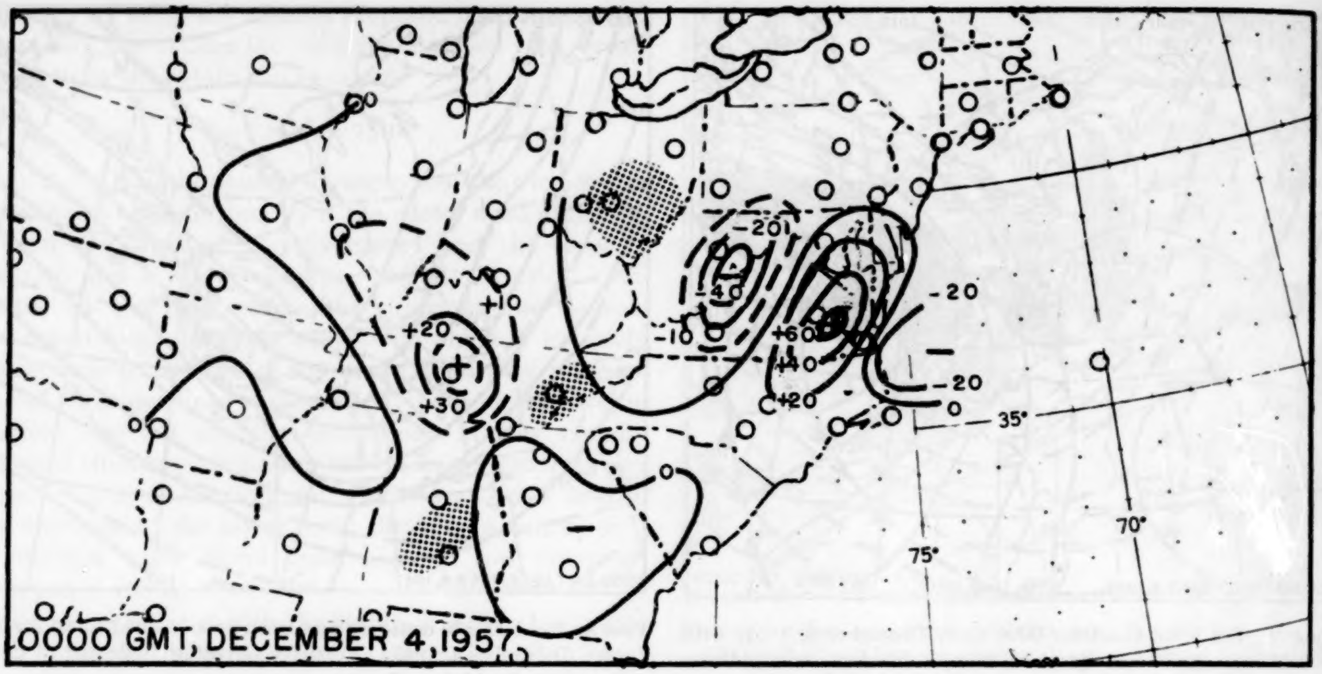

FIGURE 7.—Laplacian of thermal advection computed from surface geostrophic winds and 1000–500-mb. thickness, in units 10^{-9} sec^{-2}. Shaded areas represent 6-hour precipitation amounts greater than 0.25 inch ending at 0000 GMT, December 4, 1957.

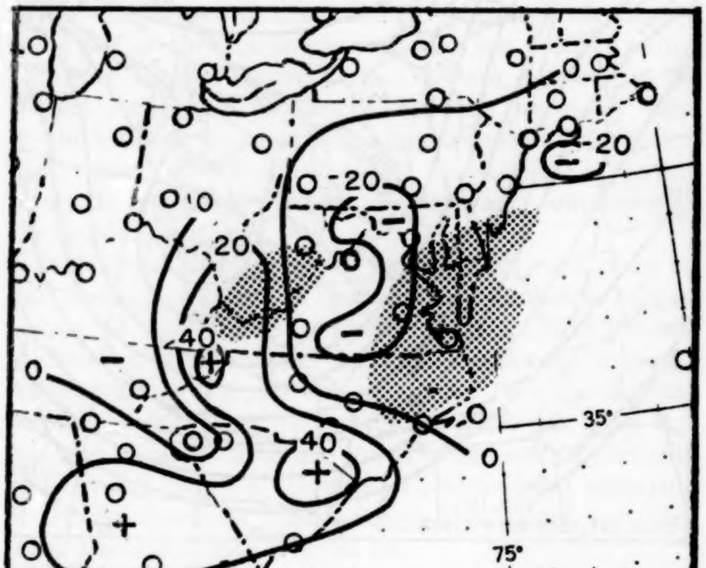

FIGURE 8.—Laplacian of thermal advection computed from surface geostrophic winds and 1000–500-mb. thickness, in units 10^{-9} sec^{-2}. Shaded areas represent 6-hour precipitation amounts greater than 0.25 inch ending at 1200 GMT, December 4, 1957.

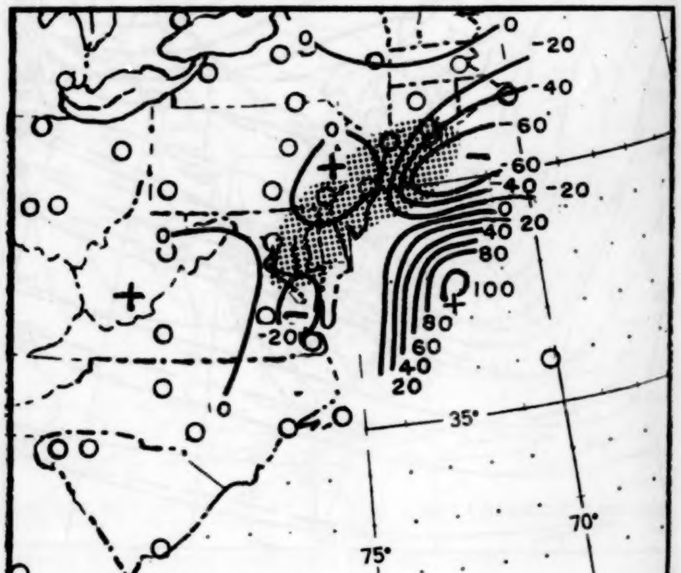

FIGURE 9.—Laplacian of thermal advection computed from surface geostrophic winds and 1000–500-mb. thickness, in units 10^{-9} sec^{-2}. Shaded areas represent 6-hour precipitation amounts greater than 0.25 inch ending at 0000 GMT, December 5, 1957.

(fig. 6) had already decreased appreciably over the western portion of the center, but a large negative Laplacian of thermal advection along the coast (fig. 9) was still contributing appreciably to intensification. This intensification did continue after 0000 GMT, but at a decreasing rate.

It is of interest to note that comparison of the Laplacian of thermal advection with the areas of precipitation (figs. 7, 8, 9) shows approximate agreement when the motion of the systems is considered. This is in line with the finding of other investigators (cf. [4]). Some irregularities in the pattern of the Laplacian of thermal advection over the

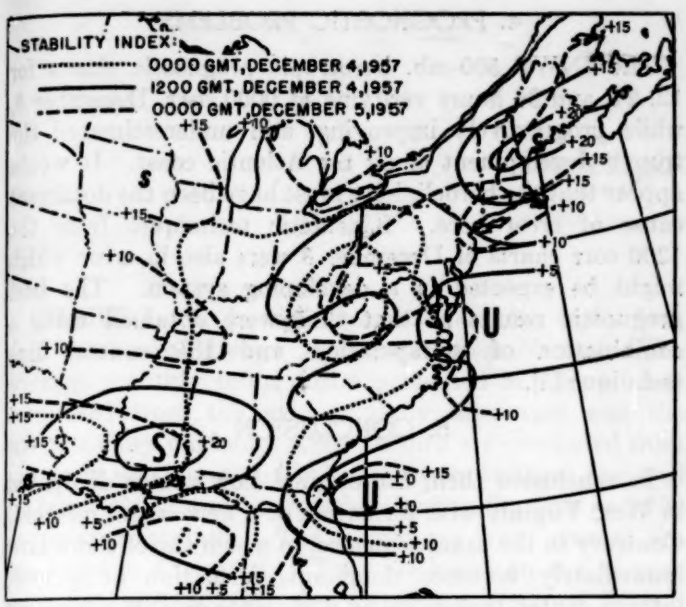

Figure 10.—Stability index chart.

mountains were due to the topography and thus would not be associated with precipitation since moisture was not available.

3. PRECIPITATION COMPUTATIONS

In an article of this scope only an estimate of precipitation could be made. Lacking even quantitative values of vertical motion, the best approach was one using only the data at hand. In addition, lack of data over the ocean area precluded anything but a simple approach. Accordingly, a method proposed by Swayne [3] was utilized. He has shown that with certain simplifying assumptions the precipitation rate is proportional to the moisture advection. First it is necessary to convert the precipitable water to "saturation thickness." This is defined as the thickness between specified constant pressure surfaces of a saturated column having the same precipitable water value as the observed column. It is then assumed that the thickness lines in saturated areas are fixed for the duration of the precipitation. In this case, as has been found elsewhere, the changes were negligible—at least in the area where computations were made for the periods concerned. Then, for the special case of unsaturated air, using the mid-layer geostrophic wind and ignoring vertical moisture transport other than that implied by the fact that the thickness lines are not advected in the precipitation areas, it can be shown, with some further simplifications, that the rate of precipitation is proportional to the area formed by the grid of thickness lines and contours.

Computations were made for each of the four 6-hour periods beginning at 0000 GMT on December 4 and continuing through 0000 GMT, December 5, using the 1000–700-mb. thickness and the 850-mb. contours. Since the contour field could not be drawn for 0600 and 1800 GMT, the actual winds were used. The difference between actual contours and contours implied by the winds is, in this case, within the limitations of the method itself. To obtain a more representative verification, the precipitation amounts were taken 3 hours either side of the computation times. Results are shown in table 1, for the Washington, Baltimore, and New York stations where hourly values and intermediate winds aloft were available. Some of the larger discrepancies could be qualitatively accounted for.

The computation for 0000 GMT, December 4 at Washington was closely approximated 40 miles southeast at

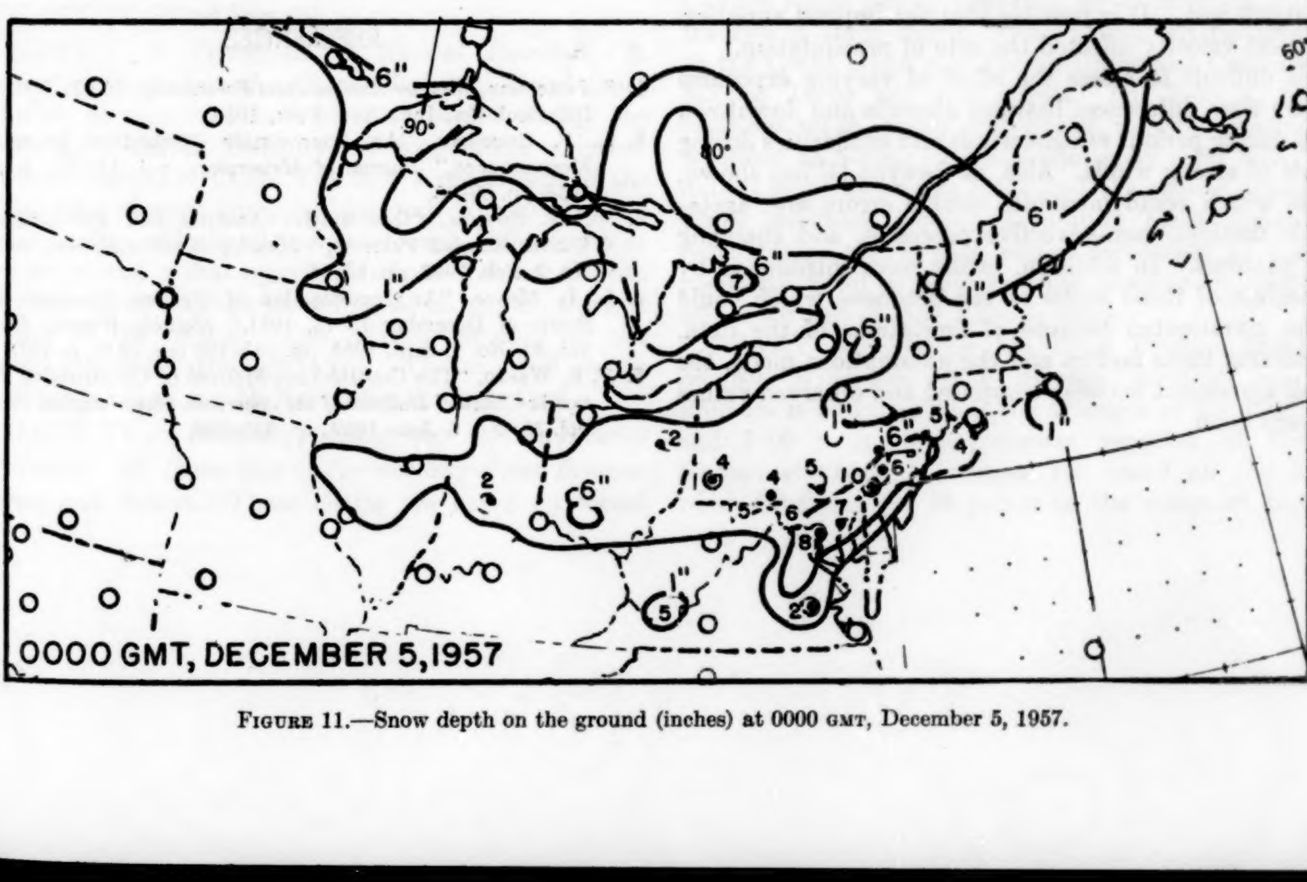

Figure 11.—Snow depth on the ground (inches) at 0000 GMT, December 5, 1957.

TABLE 1.—*Computed and observed 6-hour precipitation amounts*

Date GMT	Computed	Observed				Computed	Observed		
		Washington, D. C.		Baltimore, Md.			New York, N. Y.		
		City office	Airport	City office	Airport		City office	La Guardia	Central Park
Dec.									
4th 0000	0.24	0.02	0.02	0.03	0.03	0.03	0.01	0.02	T
4th 0600	.18	.17	.04	.17	.10	.35	.24	.18	.20
4th 1200	.00	.31	.26	.29	.21	.36	.13	.09	.05
4th 1800	.27	.42	.62	.31	.25	.48	.36	.40	.39
5th 0000	.00	.08	.19	.03	.07	.15	.15	.26	.10
Total	.57	1.00	1.13	.83	.66	1.37	.89	.95	.74

Patuxent, Md., which reported .33 inch in the period ending at 0600 GMT, or 6 hours after computation time. This value seemed fairly representative of the area just to the south. At 0000 GMT on the 5th, in connection with the computed and observed values, the precipitation stopped within one hour after the computation time in the Washington-Baltimore area. At 1200 GMT on the 4th, the 850-mb. Low was centered directly over the Washington-Baltimore area but the Low centers at higher levels were still to the west. Inspection of the Washington winds showed no appreciable cross-thickness flow at any level below the 700-mb. level. Computations for a deeper layer were not made as there were considerable variations in the hourly amounts. While city office values for both Washington and Baltimore were evenly distributed throughout the period, bracketing the computations, both airports showed that nearly all of the precipitation, .20 inch in each case, fell in the last 2 hours. Surface winds were still light at this time so that varying exposures do not account for the difference. Also at 1200 GMT, in the New York area, inspection of the upper winds showed apparent cold advection between 12,000 and 20,000 feet. It is possible that the implied variation in vertical velocity affected the rate of precipitation.

It is difficult to assess the effect of varying exposures as there were differences between airports and downtown offices during periods of light winds and similarities during periods of strong winds. Also, as Swayne [3] has shown, factors which could introduce sizable errors are: ageostrophic motions, non-advective processes, and changing wind patterns. In addition, errors were introduced by the neglect of those scales of the processes which could not be investigated because of limitations of the data. Considering these factors and the assumptions made, the overall agreement between computed and observed values was very good.

4. PROGNOSTIC PROBLEMS

The JNWP 500-mb. barotropic prognostic charts for 12, 24, and 36 hours verifying at 0000 GMT, December 5, while progressively improving, still underestimated the trough development along the Atlantic coast. It would appear that the baroclinicity must have been the dominant cause of error here. Kinematic techniques from the 1200 GMT charts of December 3 were also in error which might be expected in a developing system. The best prognostic results at that time were obtained using a combination of extrapolation and the control line technique [5].

5. CONCLUSION

In conclusion then, the original Low center dissipated in West Virginia with formation of a new center offshore. Contrary to the usual sequence, in which the offshore Low immediately becomes dominant, formation of a new, intense center took place in a climatologically infrequent location—extreme northwestern North Carolina—as the area of maximum vorticity advection became superimposed on a favorable thermal field. This new center moved offshore and became the dominant Low, only slowly beginning to merge with the first offshore center after precipitation stopped in the area of heaviest snowfall. Rates of snowfall were light but the intensification of the second system allowed snow to continue 24 hours in places, with resulting large accumulations.

ACKNOWLEDGMENTS

The authors wish to thank the staff of the Daily Map Unit for drafting the illustrations and members of NAWAC for helpful suggestions and assistance.

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4. L. L. Means, "An Investigation of Cyclone Development—Storm of December 13–15, 1951," *Monthly Weather Review*, vol. 83, No. 9, Sept. 1955, pp. 185–198 (eq. (2.6), p. 197).
5. P. E. Wasko, "The Control-Line Method of Constructing Prognostic Charts," *Bulletin of the American Meteorological Society*, vol. 33, No. 6, June 1952, pp. 233–236.

Description of Charts

CHART I. A. *Average Temperature (°F.) at Surface. B. Departure of Average Temperature from Normal.*—The average monthly temperature presented in Chart I-A is computed from the average daily maximum and the average daily minimum which in turn are computed from the daily maximum and minimum temperatures reported by some 225 first-order Weather Bureau Stations and 700 cooperative stations. The departures from normal are presented in Chart I-B. They are based on the 30-year normals (1921–50) for the first-order Weather Bureau stations and on means of 25 years or more (mostly 1931–55) for the cooperative stations.

CHART II. *Total Precipitation.*—

CHART III. A. *Departure of Precipitation from Normal (inches). B. Percentage of Normal Precipitation.*—Chart II is based on daily precipitation records at about 800 Weather Bureau and cooperative stations. In chart III the anomaly in the month's precipitation is shown as a departure from the normal total and as a percentage of the normal total. These anomalies show the deviations from the 30-year normals (1921–50) for about 225 first-order Weather Bureau stations in Charts III A and B, supplemented in Chart III-A by the deviation from means of 25 years or more (mostly 1931–55) for about 700 cooperative stations.

CHART IV. *Total Snowfall.*—

CHART V. A. *Percentage of Normal Snowfall. B. Depth of Snow on Ground.*—Chart IV gives the total depth in inches of unmelted snowfall as reported during the month by Weather Bureau and cooperative stations. This is converted in Chart V-A into a percentage of the normal total amount computed for each Weather Bureau station having at least 10 years of record. The depth of snow on ground is that reported by both Weather Bureau and cooperative stations as of 7:00 a. m. EST on the last Monday of the month. This is reported only for the months December through April. The snowfall charts are presented each month November through April.

CHART VI. A. *Percentage of Sky Cover Between Sunrise and Sunset. B. Percentage of Normal Sky Cover Between Sunrise and Sunset.*—These charts are based on visual observations made hourly at Weather Bureau stations and averaged for the month. Sky cover includes, in addition to cloudiness, obscuration of the sky by fog, smoke, etc. Normal amount of sky cover is computed for stations having at least 10 years of record.

CHART VII. A. *Percentage of Possible Sunshine. B. Percentage of Normal Sunshine.*—Chart VII-A shows the amount of sunshine received in terms of percentage of the total hours of sunshine possible during the month. In Chart VII-B this is shown as a percentage of the normal number of hours of sunshine received; normals are computed for Weather Bureau stations having at least 10 years of record.

CHART VIII. *Average Daily Values of Solar Radiation, Direct and Diffuse.*—Plotted on the chart are the monthly means of daily total solar radiation, both direct and diffuse, in langleys (gm. cal. $cm.^{-2}$) for all Weather Bureau stations which record this element. Supplementary data, for which limits of accuracy are wider than for those data shown, are drawn upon in making the analysis. The inset shows the percentages of the mean based on the period 1951–55.

CHART IX. *Tracks of Centers of Anticyclones at Sea Level.*—

CHART X. *Tracks of Centers of Cyclones at Sea Level.*—Centers which can be identified for 24 hours or more are tracked in these charts. Semi-permanent features such as the Great Basin and Pacific Highs and Colorado and Mexico Lows are not shown. The 7:00 a. m. EST positions are shown by open circles, with the intermediate positions at 6-hour intervals shown by solid dots. The date is given above the circle and the central pressure to whole millibars below. A dashed track indicates a regeneration rather than actual movement to the next position. Solid squares indicate position of stationary center for period shown beside them.

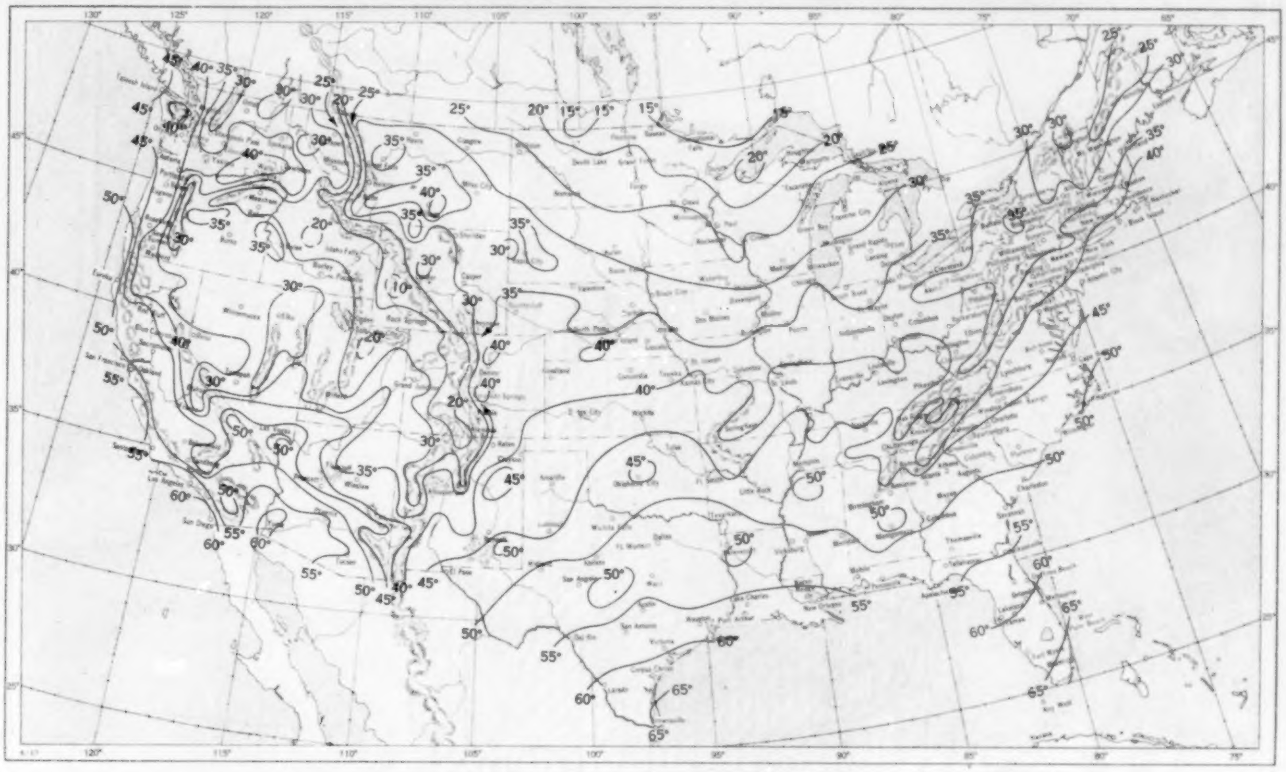
CHART XI. *Average Sea Level Pressure (mb.) and Surface Windroses.*—The average monthly sea level pressure is obtained from the averages of the 7:00 a. m. and 7:00 p. m. EST pressures reported at Weather Bureau stations. Windroses are based on the hourly wind directions (to 16 points of the compass) reported

by Weather Bureau stations, each circle or arc indicating 5 percent of the time. The inset shows the departure of the average pressure from the normal average computed for each station having at least 10 years record and for each 10° intersection in a diamond grid over the oceans from interpolated values read from the Historical Weather Maps for the 20 years of best coverage prior to 1940.

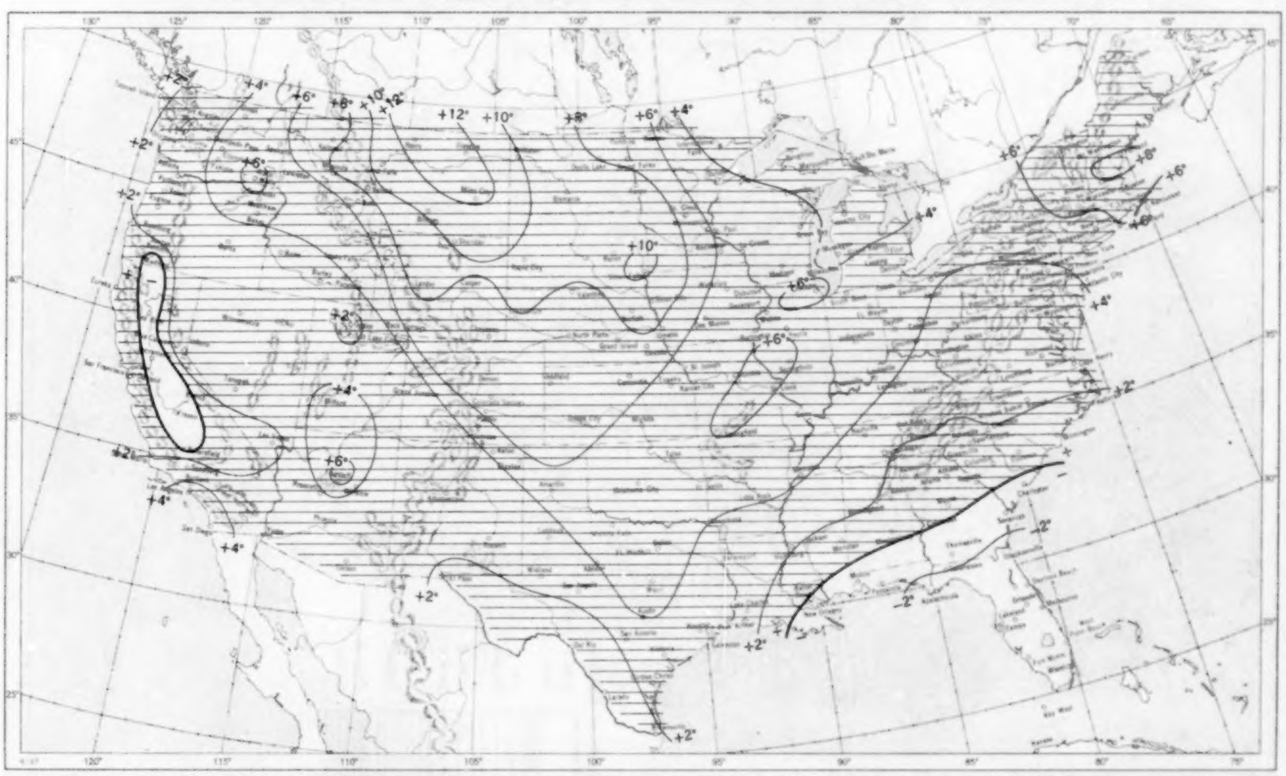
CHARTS XII-XVII. *Average Height, Temperature, and Resultant Winds, 850, 700, 500, 300, 200, and 100 mb.*—Height is given in geopotential meters and temperature in degrees Celsius. These are the averages of the 1200 GMT radiosonde reports. Wind speeds are given in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Directions are shown to 360° of the compass. Winds are based on rawins at 1200 GMT.

NOTE. Tabulations of exact values of most of these charted elements for Weather Bureau stations are printed each month in *Climatological Data—National Summary,* and annual averages are presented in the Annual Issue of that publication each year.

Chart I. A. Average Temperature (°F.) at Surface, December 1957.



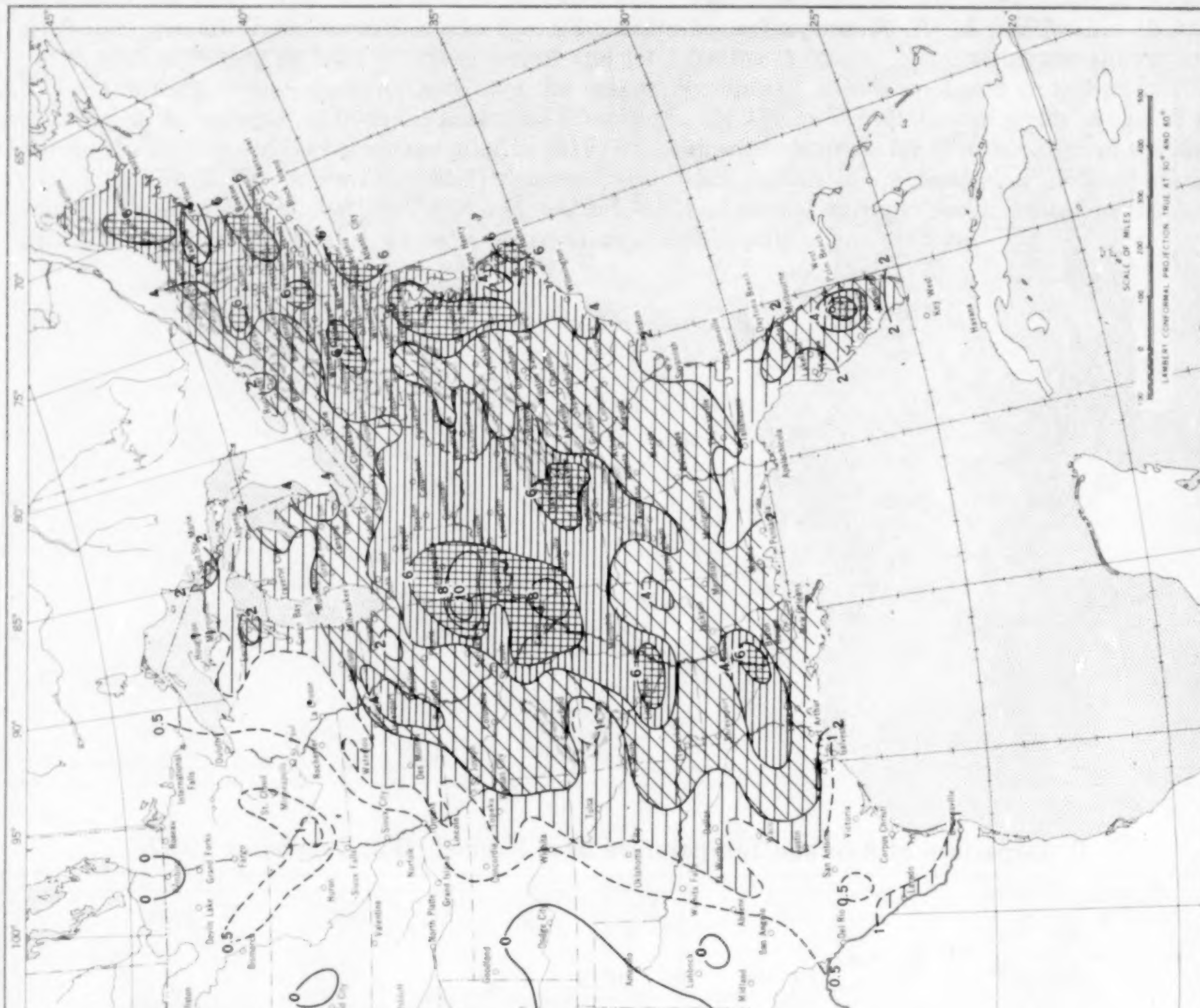
B. Departure of Average Temperature from Normal (°F.), December 1957.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

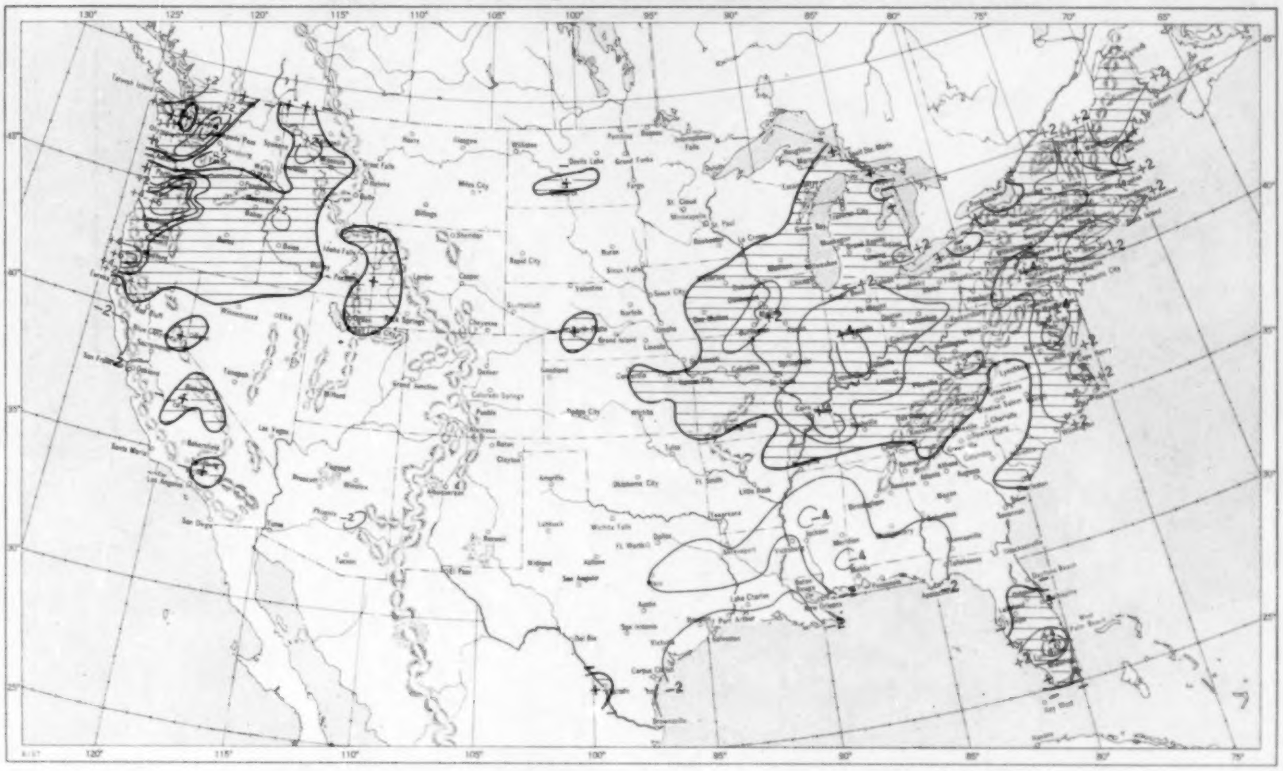
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), December 1957.

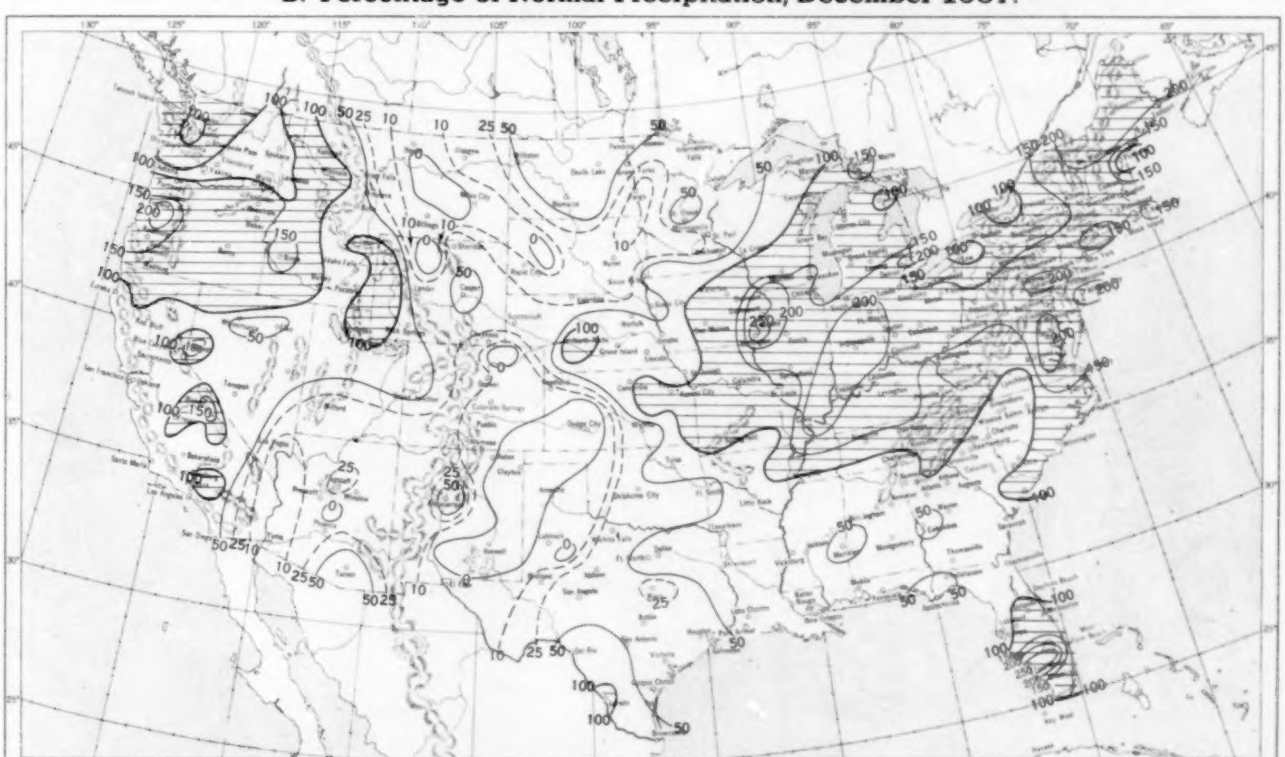


Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), December 1957.

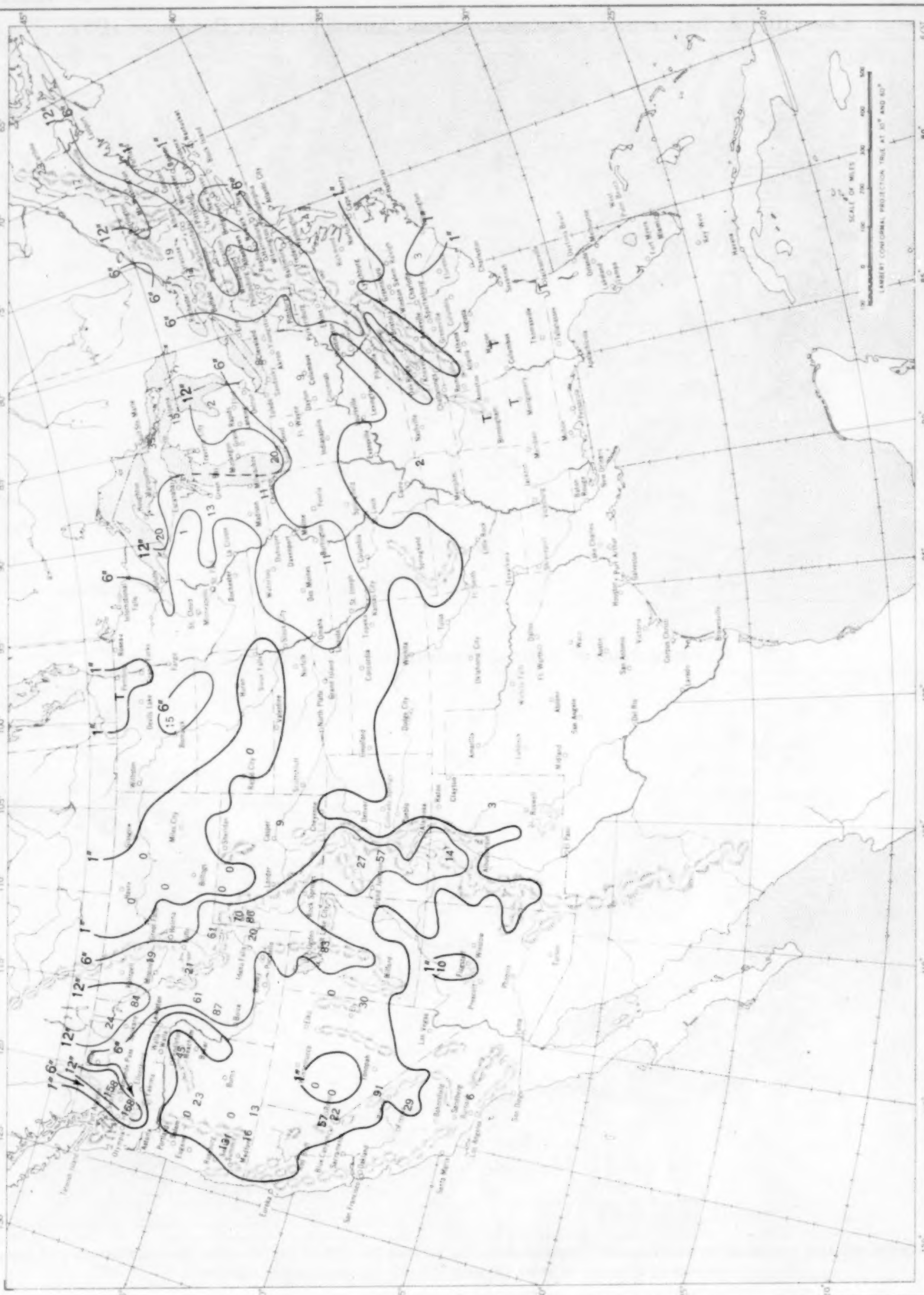


B. Percentage of Normal Precipitation, December 1957.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart IV. Total Snowfall (Inches), December 1957.



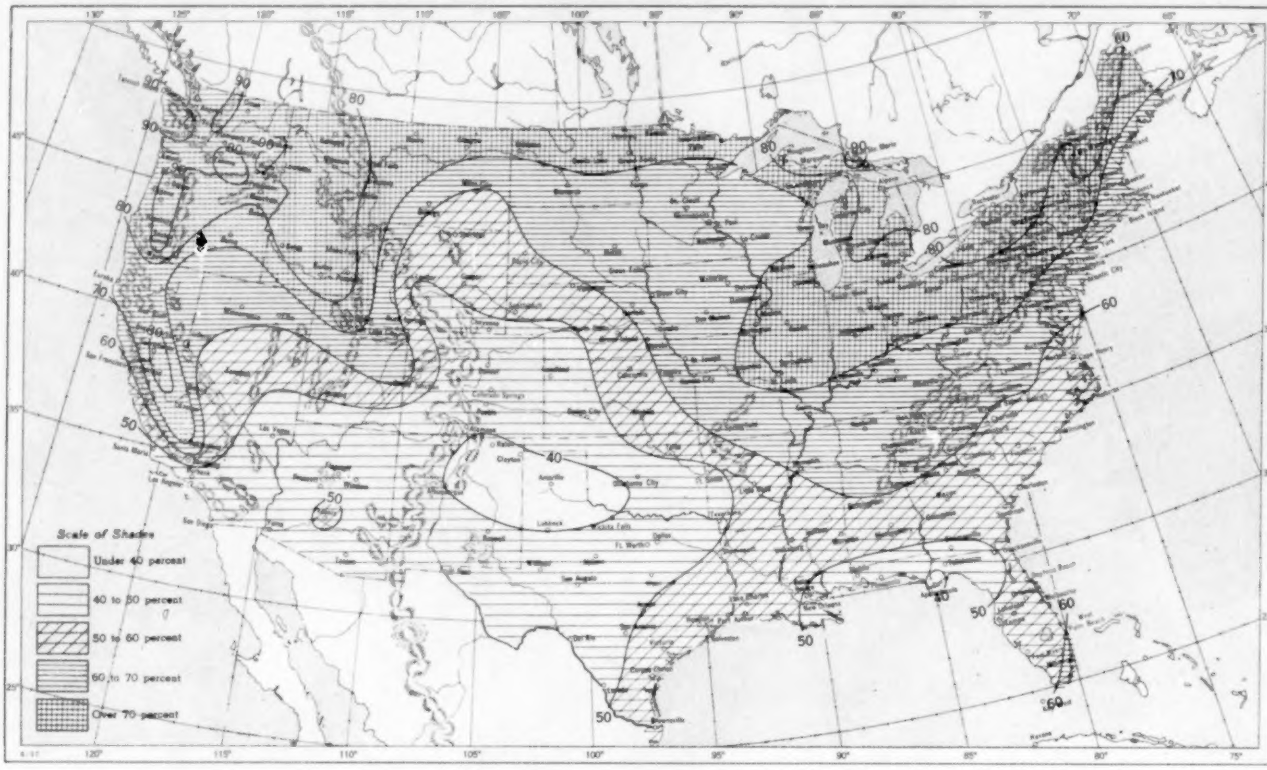
This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, December 1957.

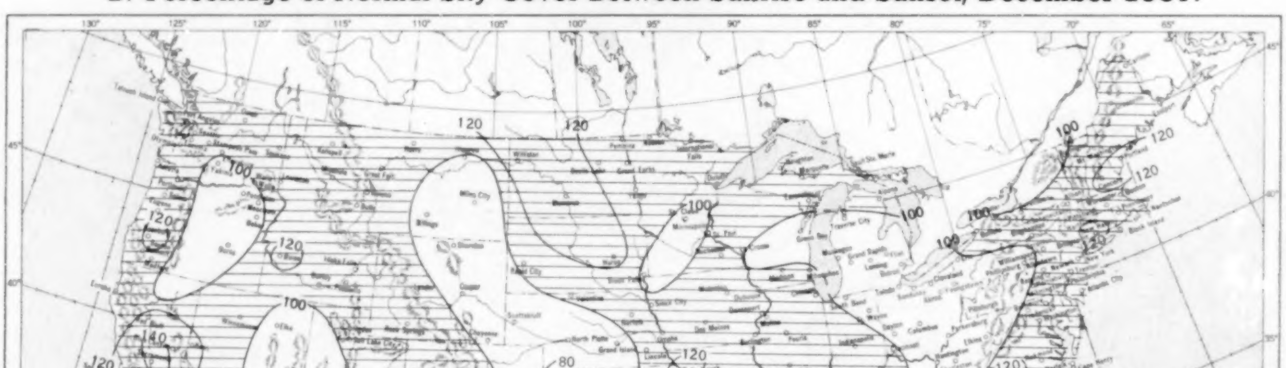
B. Depth of Snow on Ground (Inches), 7:00 a. m. E. S. T., December 30, 1957.

A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record. B. Shows depth currently on ground at 7:00 a. m. E. S. T., of the Monday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, December 1957.

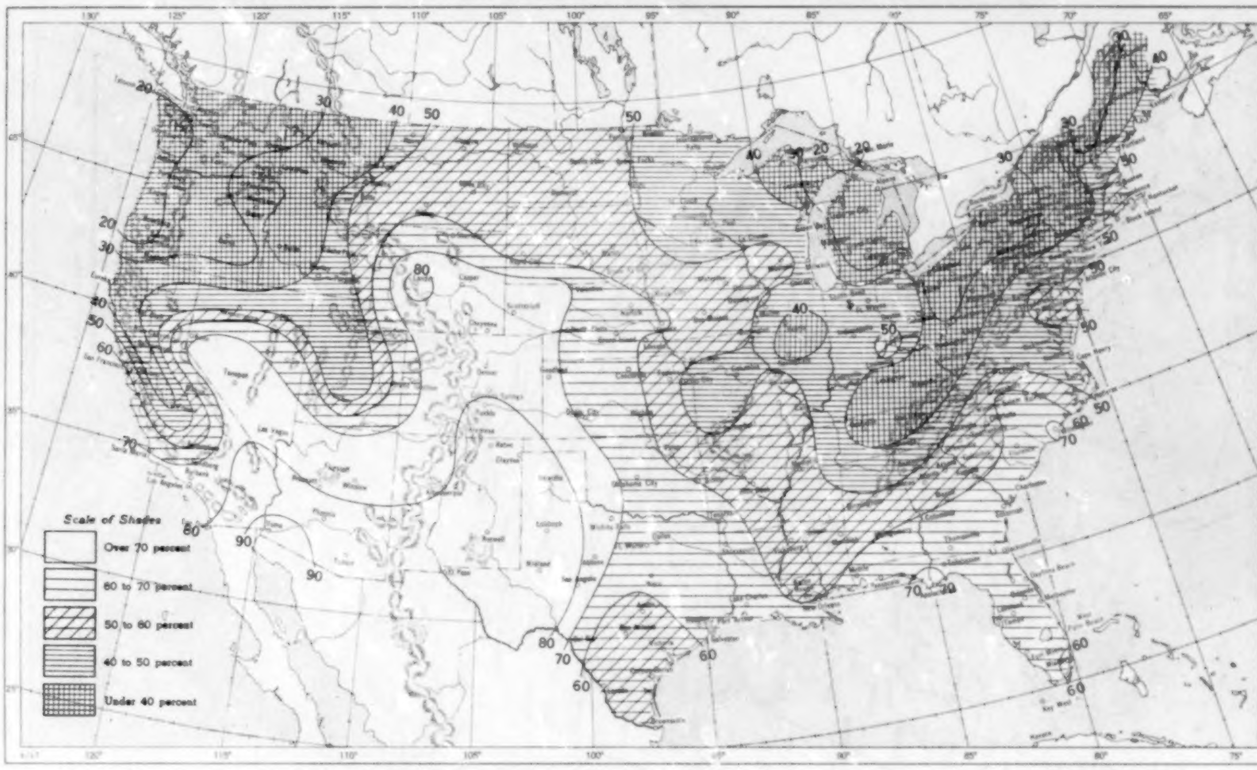


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, December 1957.

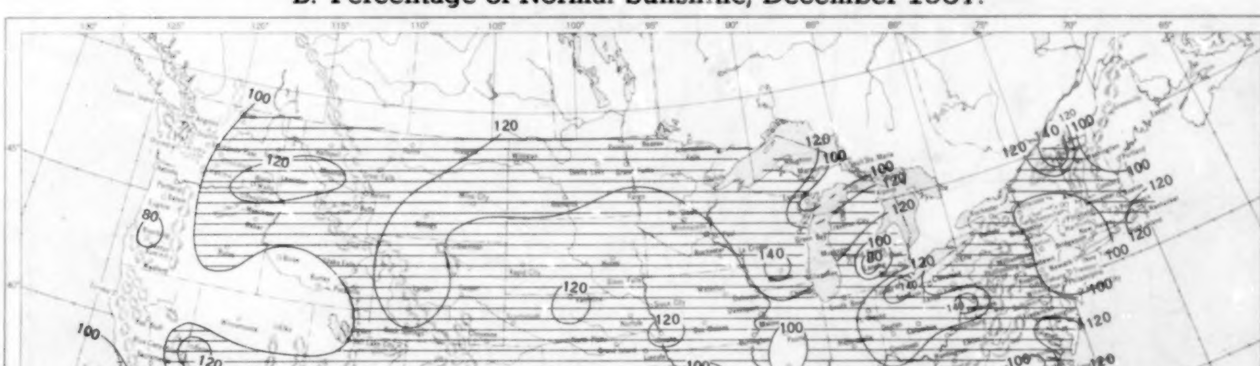


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, December 1957.



B. Percentage of Normal Sunshine, December 1957.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, December 1957. Inset: Percentage of Mean Daily Solar Radiation, December 1957. (Mean based on period 1951-55.)

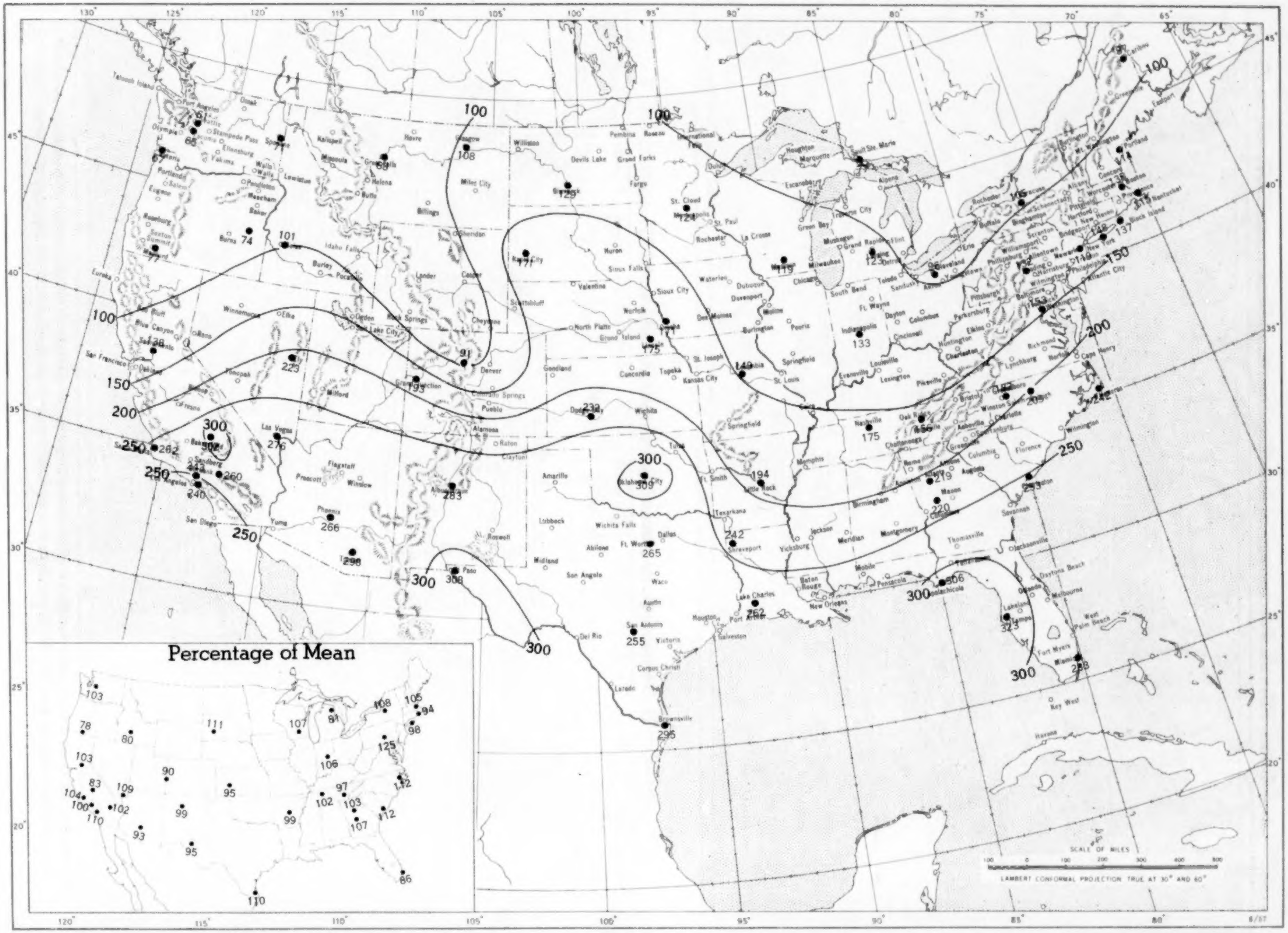
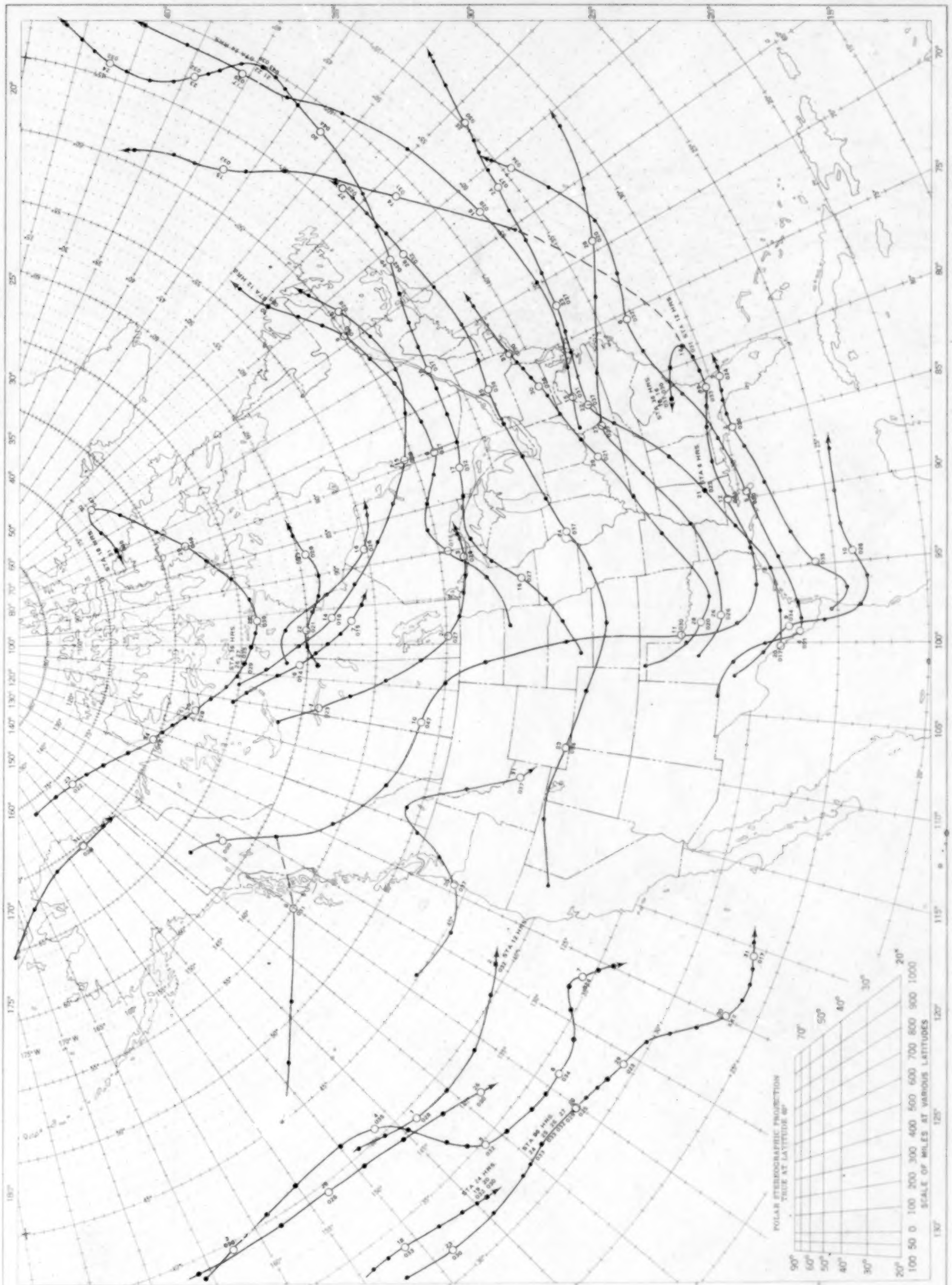


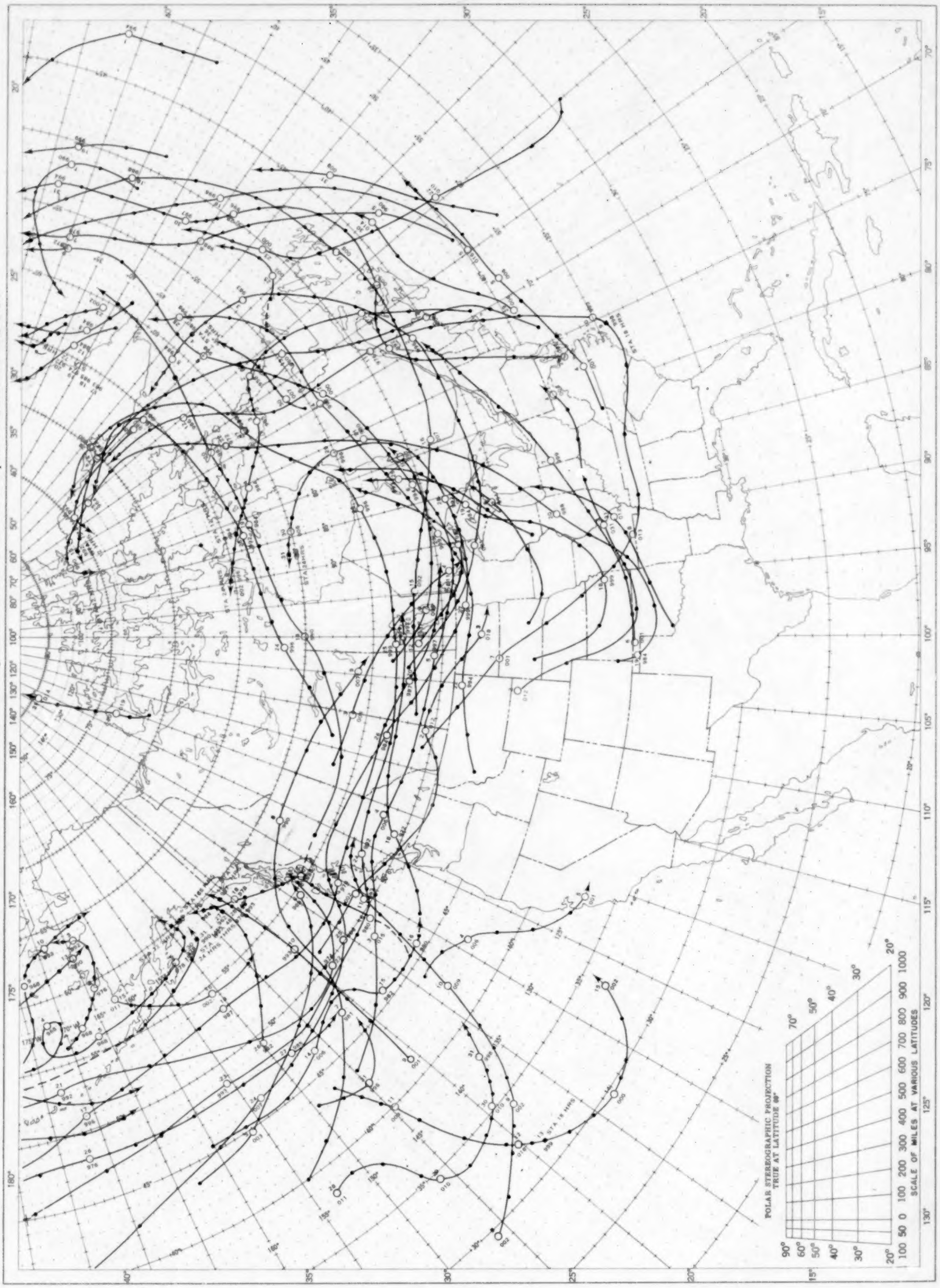
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, December 1957.



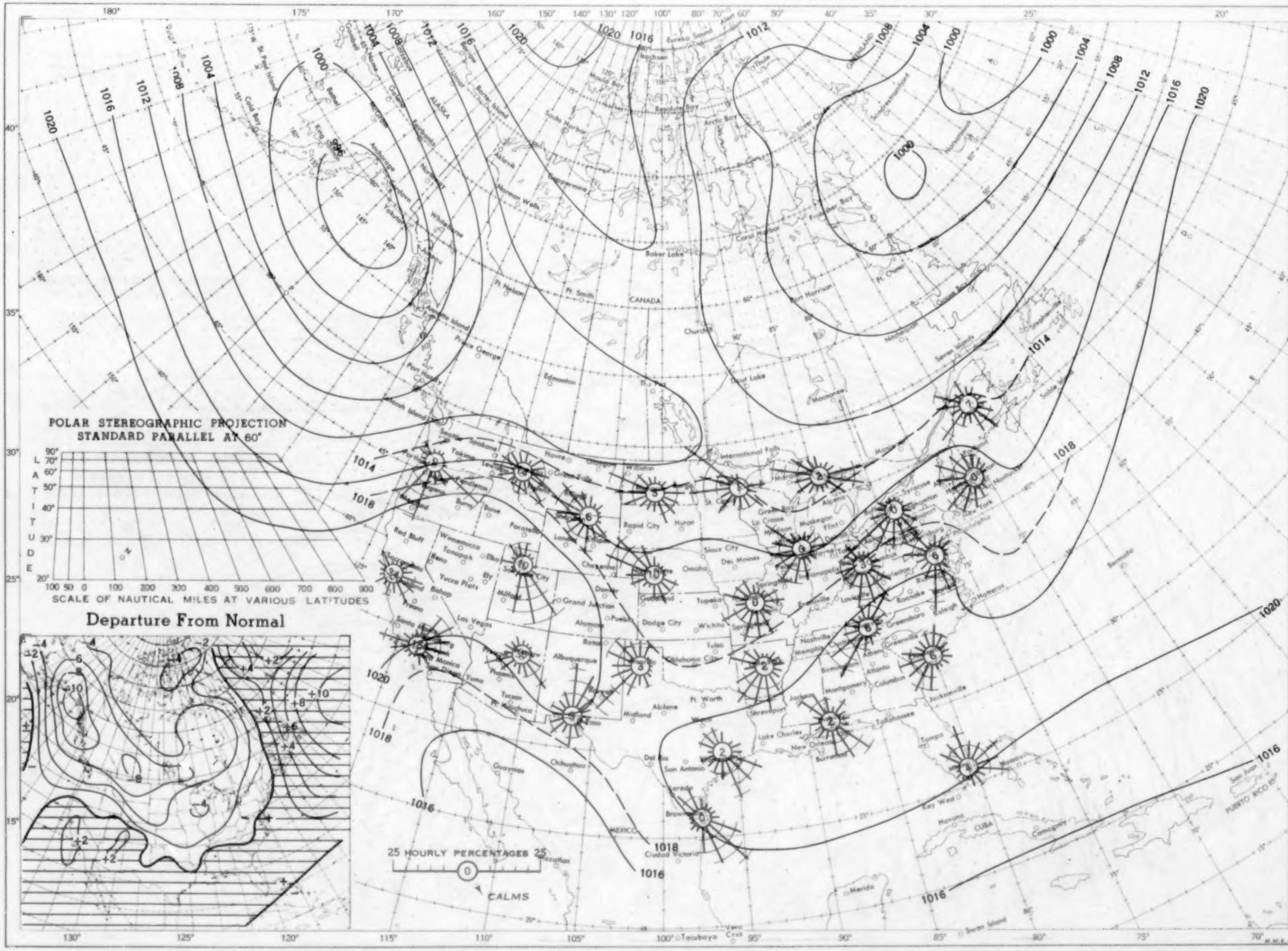
Circle indicates position of center at 7:00 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, December 1957.



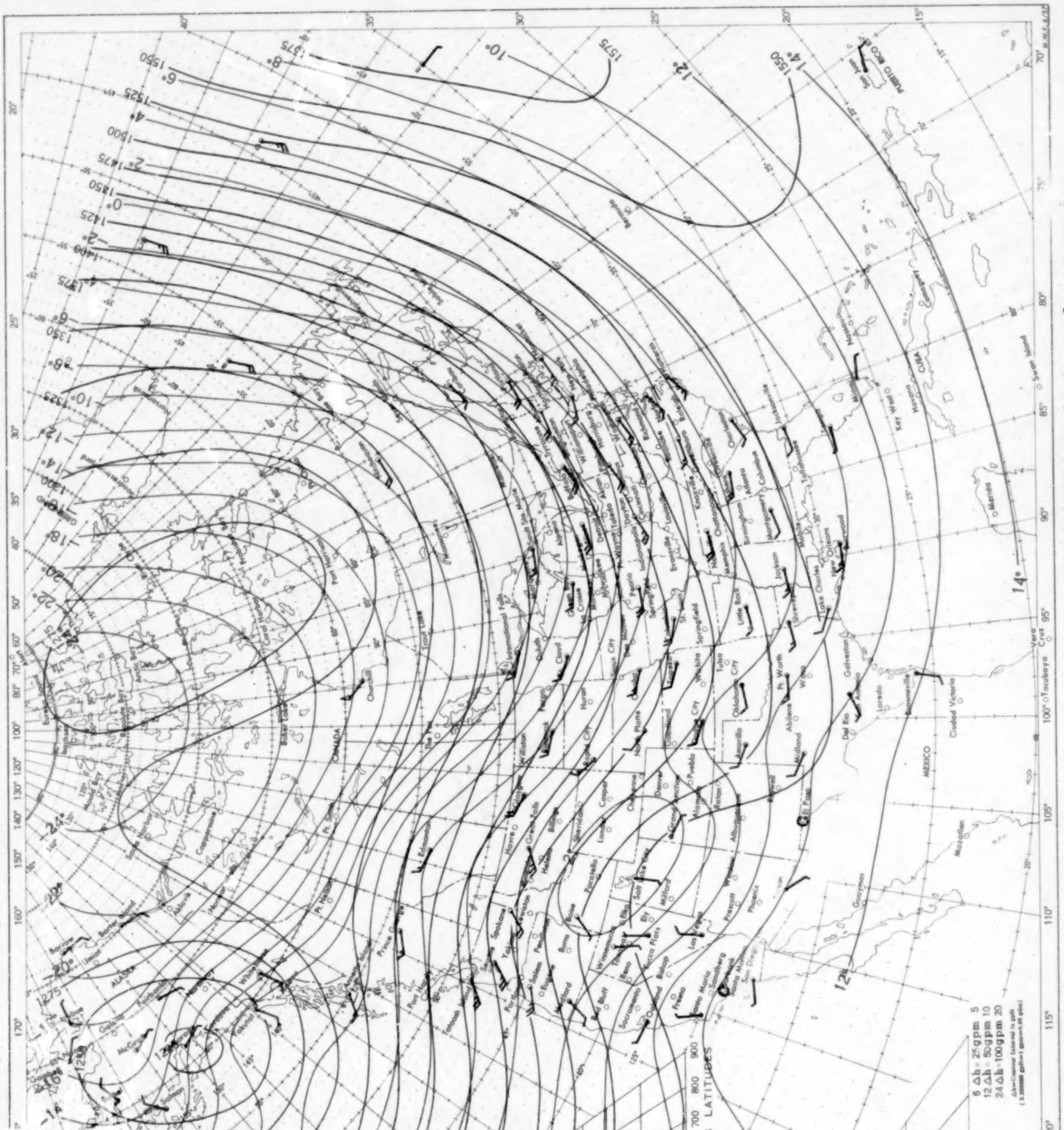
Circle indicates position of center at 7:00 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, December 1957. Inset: Departure of Average Pressure (mb.) from Normal, December 1957.



Average sea level pressures are obtained from the averages of the 7:00 a.m. and 7:00 p.m. E.S.T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, December 1957. Average Height and Temperature, and Resultant Winds.



Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. All wind data are based on rawin observations.

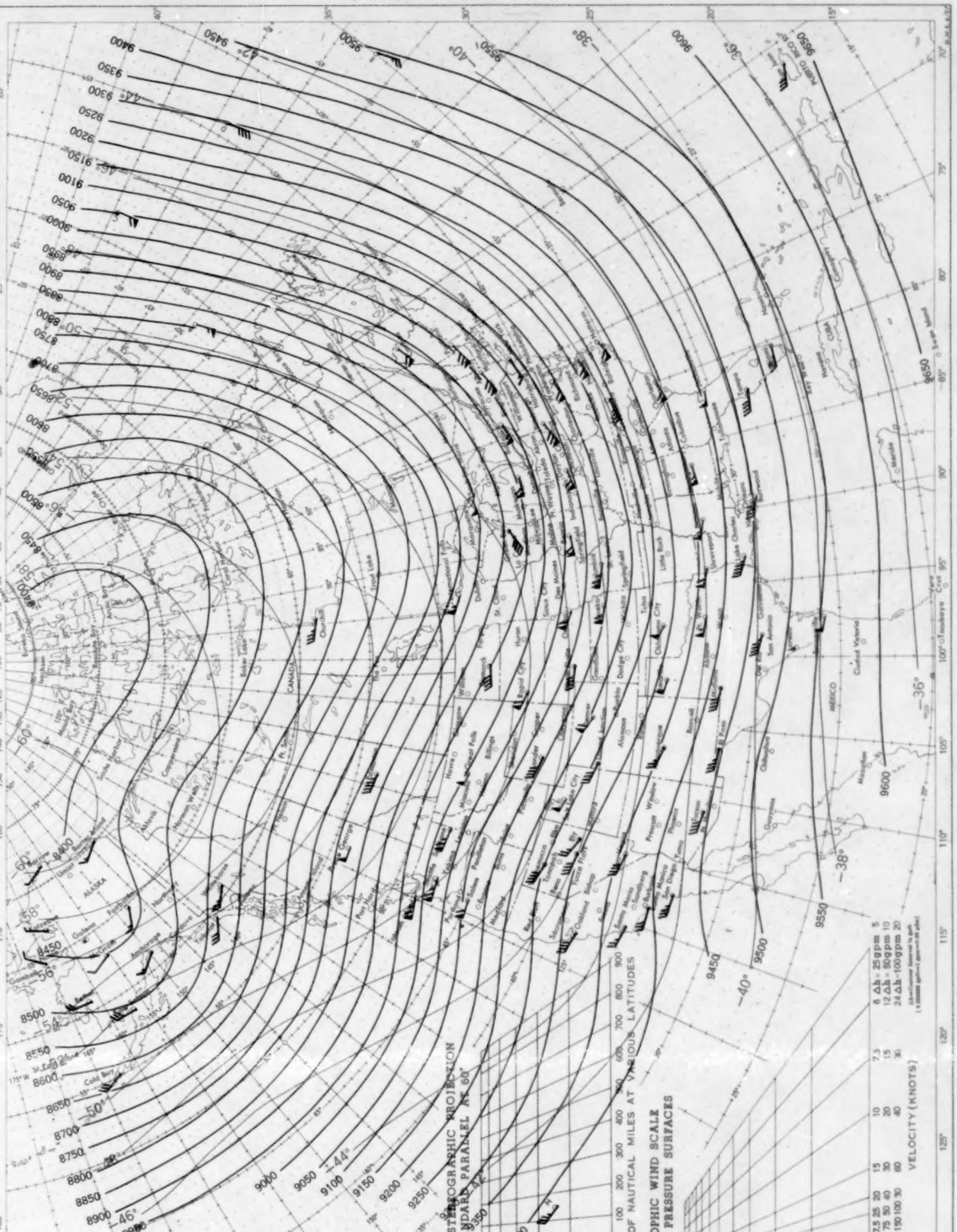
Chart XIII. 700-mb. Surface, 1200 GMT, December 1957. Average Height and Temperature, and Resultant Winds.

See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 1200 GMT, December 1957. Average Height and Temperature, and Resultant Winds.

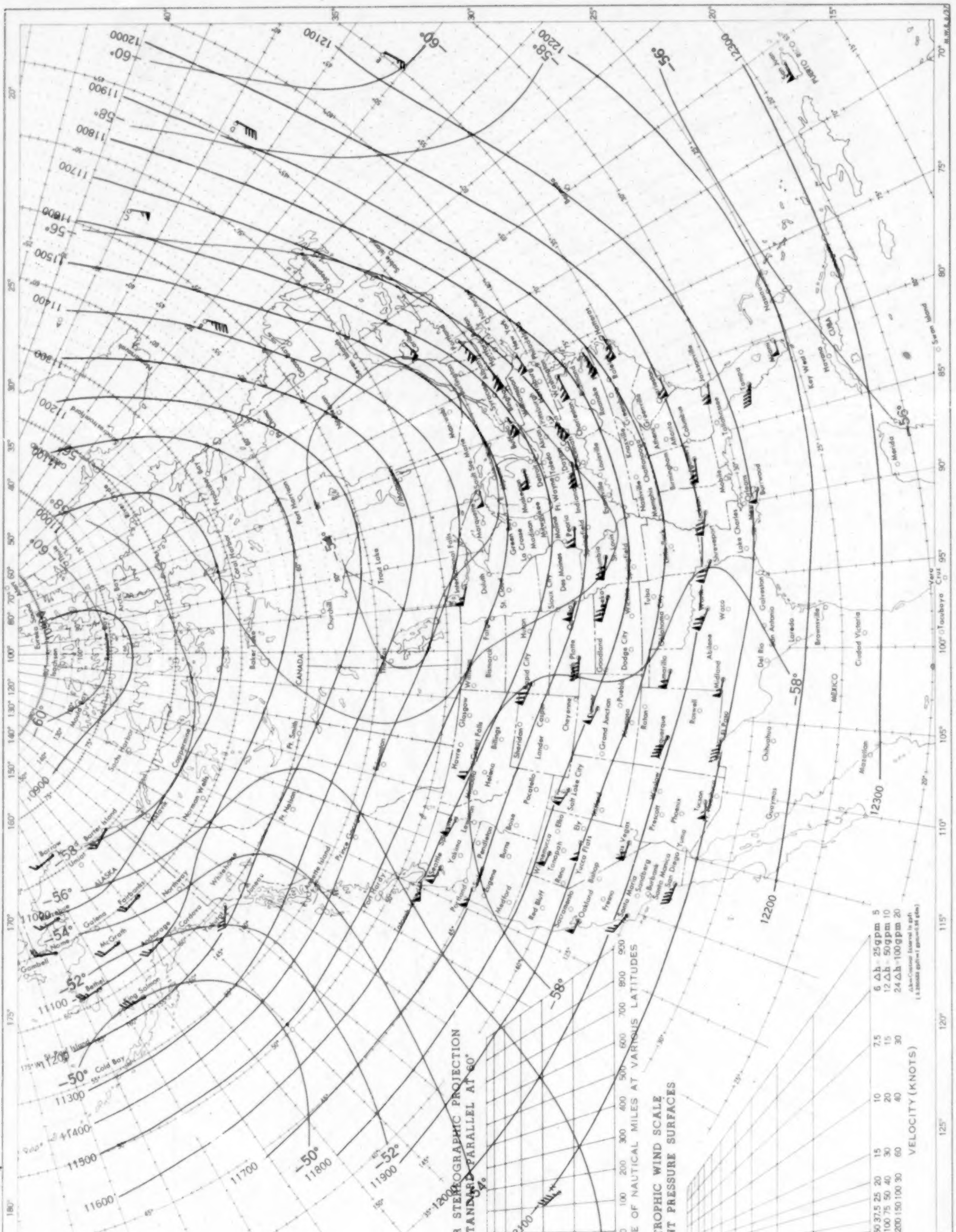
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, December 1957. Average Height and Temperature, and Resultant Winds.



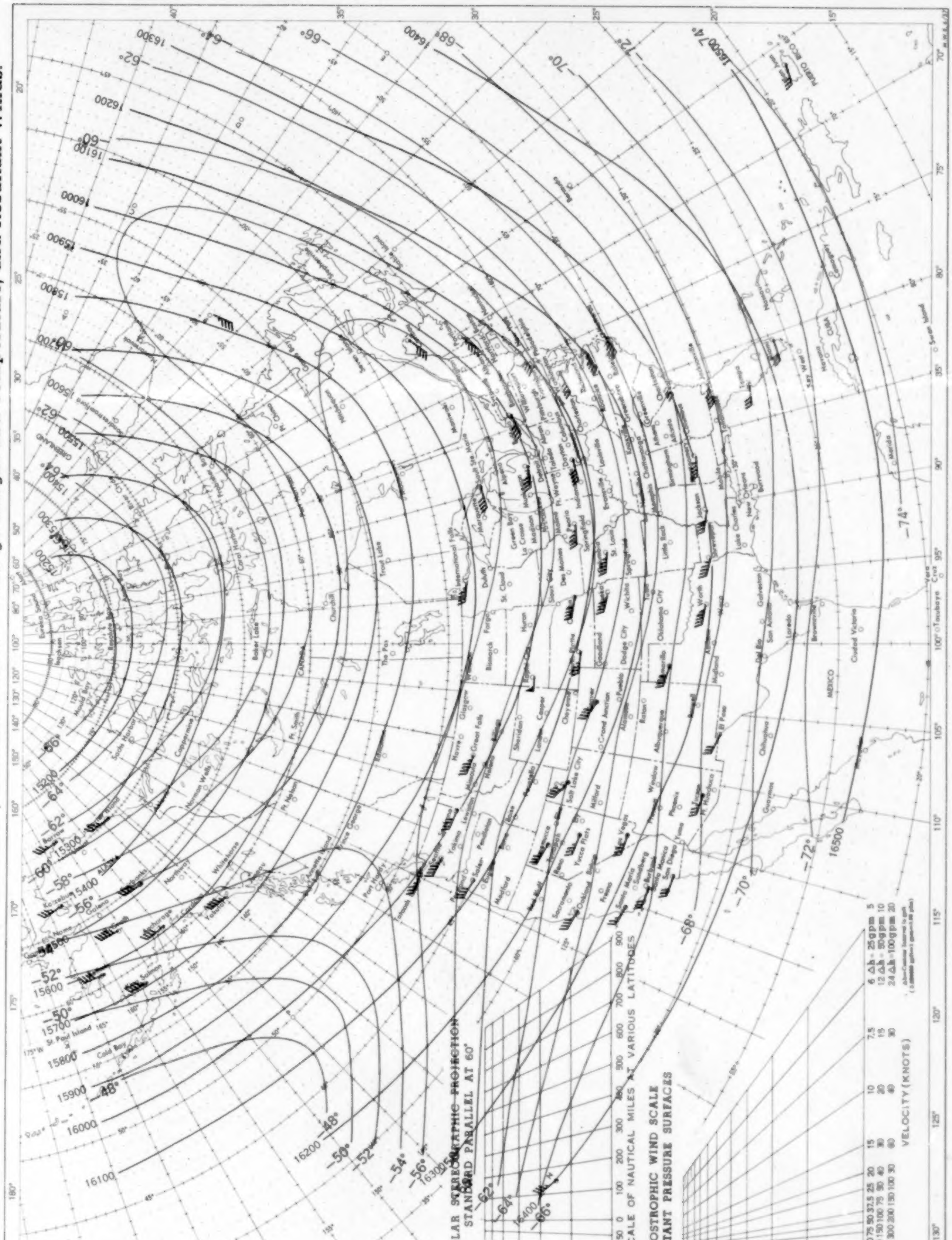
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, December 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, December 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.